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This combined teaching and study guide is for use by students and teachers in post secondary programs for nucleonics technicians. It was developed by the author under the National Defense Education Act, Title VIII. The unit headings are: (1) Physics of the Atom, (2) Natural Radioactivity and Atomic Energy, (3) Induced Radioactivity and Atomic Energy, (4) Radiation Safety and Radiation Doses, (5) Geiger-Mueller Counters, (6) Determination of Half-Life, (7) Absorption and Self-Absorption for Beta Rays, (8) Backscattering and Other Effects for Beta Rays, (9) Absorption and Inverse Square Law for Gamma Rays, (10) Resolving Time of a g-m Counter, (11) Calibration of g-m Counter End Window, (12) Statistical Variation in Radioactive Measurements, (13) Determination of Range and Energy of Alpha Particles, (14) Effect of Magnetic Fields upon Beta and Gamma Radiation, (15) Comparison of g-m, Gas Flow Proportional, and Scintillation Counters, (16) Radioactive Fallout, (17) Tracer Techniques, and (18) Cloud Chamber. Each unit gives objectives, introduction, teaching plan, apparatus required, textual material, study questions, and a bibliography. Five hours of instruction should be allotted to each of the units. The students should be high school graduates and the teachers should have had a basic course in nuclear physics. (EM)

basic course in nucleonics

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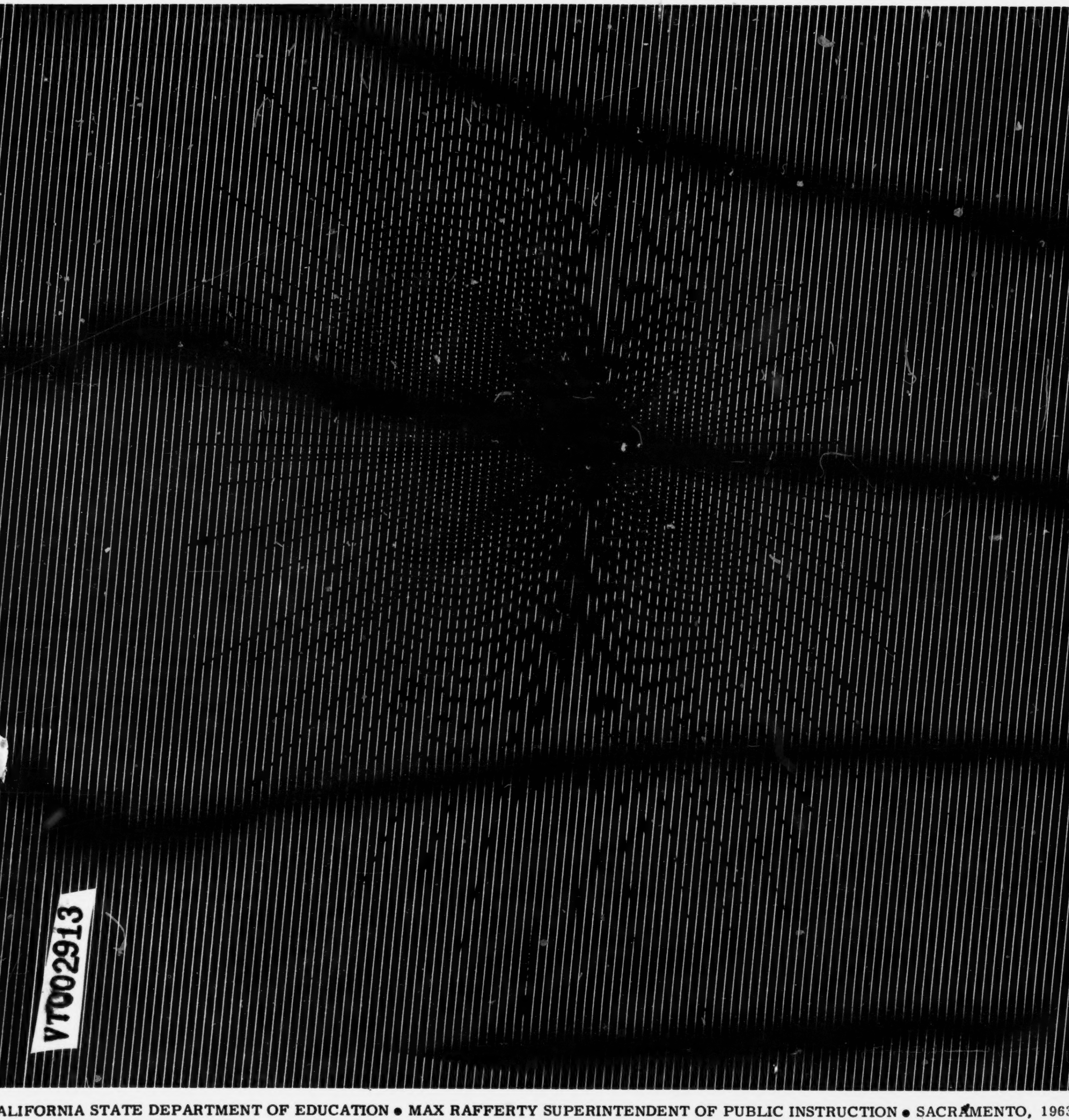

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basic course in nucleonics

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SAN MATEO

2

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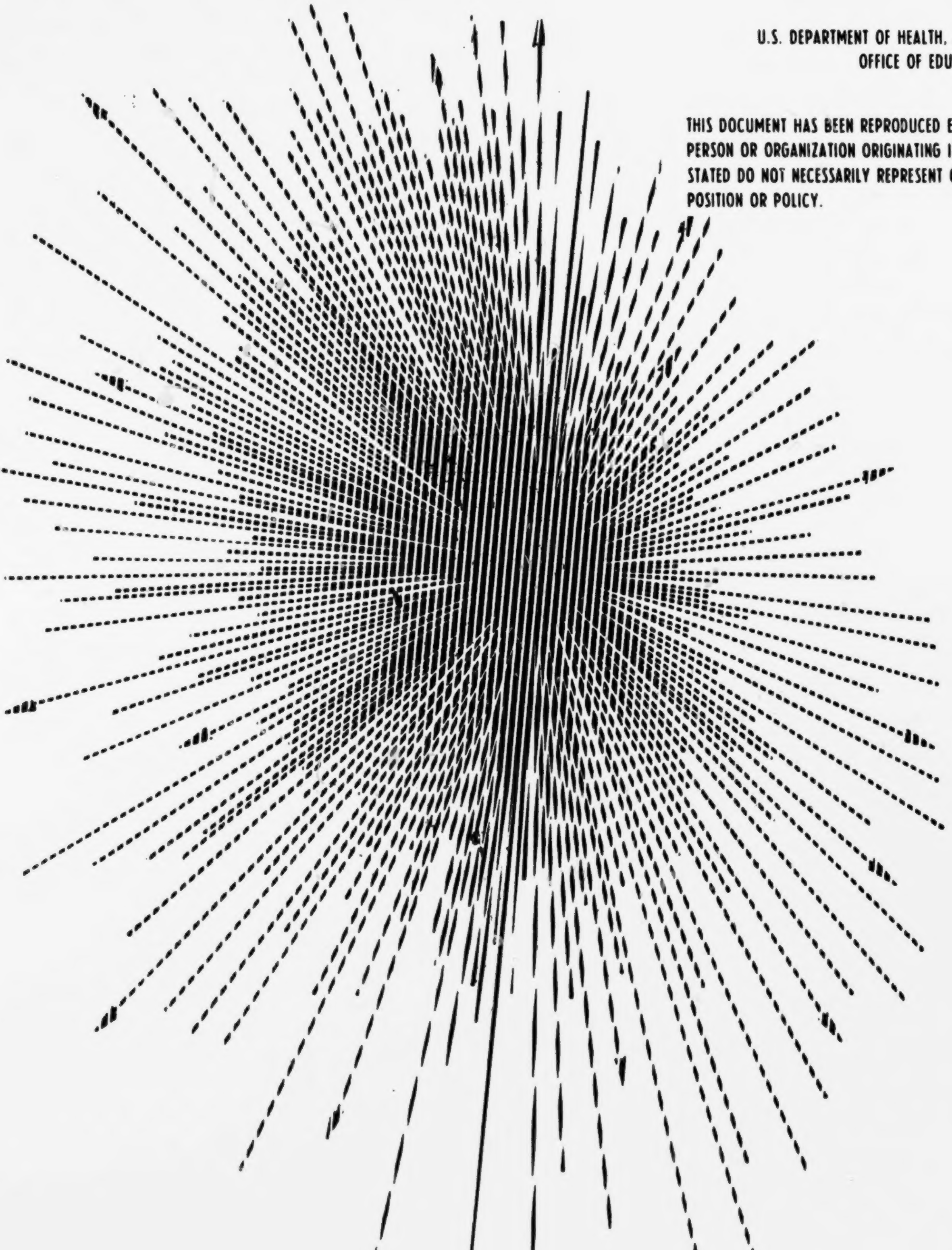

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foreword

Rapid growth in the number and types of technicians needed by California industry has become an increasingly important and complex phenomenon in the state during the past two decades. Training these technicians has become equally important and complex.

In order to provide educational programs for technicians, the junior colleges of the state have developed and currently offer a variety of technical education courses. The California State Department of Education participates in these programs by assisting wherever and whenever possible in the further development of worthwhile technical curriculums.

It is hoped that this manual on nucleonics will provide an additional source of enrichment for the occupation-centered programs of the state.

Max Rafferty

Superintendent of Public Instruction

preface

Among the various technical education curriculums in California junior colleges affected by the state's dynamic industrial growth are those in the field of nucleonics. As a consequence, well-planned and well-developed instructional materials must be made available to the schools in order to provide instruction in this and other rapidly developing technical fields.

The Bureau of Industrial Education has assisted Dr. Jacob H. Wiens in preparing this instructor's guide in nucleonics as a working draft to meet the immediate needs of classes operating at the present time. A further publication is planned in the event anticipated growth in the nucleonics field becomes a reality.

Appropriations provided under Title VIII of the National Defense Education Act of 1958 have aided in financing the project.

RICHARD M. CLOWES
Chief, Division of
Instruction

WESLEY P. SMITH
Director of Vocational Education

ERNEST G. KRAMER
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Industrial Education

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physics of the atom

PLAN OF INSTRUCTION

OBJECTIVE

1. To familiarize the student with the modern concept of the atom.
2. To study the properties of the nucleons that make up the atom.
3. To discuss the size of the atom.
4. To discuss the various kinds of atoms and what portion of the atom determines the physical structure of the atom.
5. To distinguish between the physical characteristics of the atom and the nuclear characteristics of the atom.

INTRODUCTION

1. Define units of length, time, and mass.
2. Review the definitions of force and energy.
3. Introduce the concept of energy and work.
4. Review the difference in the chemical and physical concepts concerning elements.

TEACHING PLAN

1. Define the terms such as mass, force, energy, charge, and weight.
2. Emphasize the concentration of matter in the atom in the small central portion called the nucleus and point out the vast emptiness of matter in the region between the nucleus of the atom and the electron in their orbit.
3. Review briefly the existence of electrons in orbit around the nucleus but point out that this effect is not a determining factor in the structure of the nucleus of the atom.
4. Discuss the orderliness of the structure of the atom from hydrogen through the transuranic element, pointing out the relationship between the charge of the nucleus of the atom and the number of electrons in orbit around the nucleus.
5. Introduce the concept of the electron, the proton, and the neutron as elementary building blocks in the nucleus of an atom.
6. Introduce the symbols used to describe the nucleus of an atom in terms of the charge and mass.
7. Show how it is possible to determine the number of protons and the number of neutrons in an atom from this notation.

8. Discuss the nucleon particles that have been identified and relate these particles to the particles that make up the stable atom.

APPARATUS

None required.

RESOURCE MATERIAL

Physics has been called the science of measurement. The field of nucleonics is, therefore, the science of measurement of the nuclides that make up the atom. In order to make measurements, it is necessary to specify the quantity and the magnitude of the measuring unit. All physical measurements consist of a quantity and a unit, such as 45 kgm, where 45 indicates the quantity and kgm stands for kilogram, the unit of measure.

All physical measurements are based upon three independent and arbitrarily defined quantities: mass, length, and time. These arbitrary standards have been accepted by scientists; most of the measurements in the scientific world are based upon them.

The international standard of mass is a platinum-iridium cylinder and is called the standard kilogram (abbreviated kgm). A convenient unit used for many purposes is that of the gram, or one thousandth of a kilogram. The pound mass, a unit commonly used, is defined as 0.453592 kgm.

The unit of length is called the standard meter and is the distance between two lines engraved on a platinum-iridium bar. The yard, again commonly used, is now defined as one yard = 0.9144 meter.

The third fundamental unit is based on our rotating earth and is that of the mean solar day, the average time for the earth to make one rotation on its axis with respect to the sun. The length of the solar day increases and decreases gradually in the course of a year, and the length of a solar day must be averaged over a year. The day is further divided into twenty-four hours, sixty minutes, and sixty seconds to give the convenient unit of one second.

All other units in physics are based on these three units. For instance, velocity is defined as the distance covered by a particle divided by the time interval. The unit of velocity is a unit of length divided by a unit of time, such as meters/second or centimeters/second. All bodies either remain at rest or move with constant velocity in a straight line unless they are acted upon by a force. A force is defined as a push or a pull. A force will either change the motion of a particle or produce a deformity on the particle. In nucleonics the most common result is a change in the motion of the particle as a result of the electrical or electromagnetic forces on particles.

Forces between two electrical particles vary proportionally to the magnitude of the electrical charges and are inversely proportional to the square of the separation of the charges. These forces are called Coulomb forces and are represented by the equation

$$F = \frac{-e_1\, e_2}{r^2}$$

where F is the force in dynes, e_1 and e_2 are electrostatic charges in esu units of charge, and r is the separation in centimeters. The above formula is the basis for the definition of charge in electrostatic units, abbreviated esu units. There will be a repulsion force of one dyne when two similar charges with magnitudes of one esu unit are separated by one centimeter.

Electric charges that move in a magnetic field also experience a force, and this force is perpendicular to both the magnetic field and the direction in which the electric charge is moving. This causes the charged particles to move in an arc of a circle. The direction of this force will be used to prove the nature of the charge of two fundamental nuclides.

The concept of energy is used to clarify many physical phenomena. Energy is defined as the ability to do work; work is defined as the product of force and distance along the direction of the force. Thus, one formula for energy is $E = Fd$, where F is the force in Newtons, d is the distance in meters, and the energy is expressed in Joules.

Energy can be changed into many other forms but cannot be created or destroyed. Energy of motion is given by $E_k = 1/2\ Mv^2$, where M is the mass in kilograms, v is the velocity in meters per seconds, and energy is in Joules. Energy can be changed to mass and mass can be changed to energy by Einstein's equation, $E = Mc^2$, where M is the mass and c is the velocity of light, or 3×10^8 meters per second. When a charged particle e is accelerated in an electric field, the energy E that the charged particle acquires is given by $E_k = eE$. When the charged particle is a nuclide and is in units equal to the charge of an electron, the unit is given the special name of electron volts, or ev.

Energy can also be changed into heat, and heat ultimately escapes into the surrounding area by one of the three methods of heat transfer: conduction, convection, and radiation. Heat escapes into the outer atmosphere by radiation, the form of heat transfer that can be detected on the skin when near a hot object. The end results of most nuclear reactions is the production of heat.

Matter is made up of atoms. The smallest particle of matter having a distinctive chemical and physical characteristic is called an atom. Helium is an example of matter which is made up purely of separate atoms.

Atoms can combine to form larger particles of matter, and such groups of atoms are called molecules. Most of the substances that we find around us are in the form of molecules that consist of two or more atoms. The oxygen we breathe is made up of two oxygen atoms forming an oxygen molecule. The water we drink consists of two hydrogen atoms and one oxygen atom, or one water molecule. Other substances have complex molecules. Sugar, for example, consists of twelve atoms of carbon, twenty-two atoms of hydrogen, and eleven atoms of oxygen. The characteristic of matter changes with the composition of the individual atoms making up the molecule. For instance, carbon dioxide consists of one atom of carbon and two atoms of oxygen and is a by-product of all living things. Yet if one oxygen atom is removed from the molecule to leave one atom of carbon and one atom of oxygen, the molecule becomes carbon monoxide, a deadly gas. The study of atoms and the characteristics of molecules formed by combining atoms is called chemistry.

In order to save time and effort, the various atoms are given simplified symbols. Each different variety of atoms is referred to as an element and ninety-two elements are found in nature, each having a specific chemical and physical characteristic. Each element is referred to by a name and is assigned a symbol. For instance, hydrogen, the simplest element found in nature, is designated by the symbol H. Helium, the next simplest atom, is designated by the symbol He. A complete table of the elements and their symbols is found in the appendix.

Molecules, on the other hand, are designated by listing the number of atoms in each molecule, such as HCl and H_2SO_4. The first symbol indicates that the molecule consists of one atom of hydrogen and one atom of clorine. The second symbol indicates that the molecule consists of two atoms of hydrogen, one atom of sulfur, and four atoms of oxygen.

Molecules may be separated into the individual atoms that make up the molecules by chemical means. The atoms may be further separated into the primary building blocks that make up the individual atoms.

Three elementary building blocks are found in atoms. They are as follows:

The Electron

The electron is the smallest electrical particle found in nature and carries an electrical charge of 4.80288×10^{-10} esu. The magnitude of charge is such that 6.28×10^{18} electrons must pass a point in one second to produce a current of one ampere. The electron has a mass of 9.1085×10^{-28} grams.

Electrons may be created in the free state by such simple things as running a comb through the hair or by high temperature of the filament in such common devices as a television tube. In such a tube, a beam of electrons is produced and accelerated toward a screen to produce light on the screen by the collision of electrons with a surface material.

The Proton

The proton is the nucleus of the hydrogen atom and is the simplest form of matter carrying a positive charge. The proton can be produced by removing the electron from a hydrogen atom, which can be accomplished by shooting a stream of electrons into hydrogen gas. Under these circumstances, the proton will soon attract an electron and reform hydrogen gas.

The proton is approximately 1,836 times as heavy as the electron. While the hydrogen atom has a large mass compared to the electron, a total of 6.0427×10^{23} hydrogen atoms have a combined mass of 1.008142 grams (454 grams equal one pound). Each proton has a mass of 1.67243×10^{-24} grams.

The Neutron

The neutron has approximately the same mass as the proton but it has a zero charge. The mass of a neutron is 1.67474×10^{-24} grams. It can be produced by bombarding any atom with high velocity particles and almost any collision of atoms, if they are moving rapidly enough, will produce neutrons. Neutrons are short lived and will recombine with other primary particles to form other atoms.

Approximately 92 different types of atoms are generally found in nature. The atoms are numbered from 1 to 92, and the number indicates the number of electrons that revolve about the nucleus. The nucleus is the heavy, center core of an atom and contains protons equal in number to the electrons around the atom and neutrons in an amount approximately equal to the number of protons.

The radius of the atom with its electrons revolving about it is such that approximately 100,000,000 atoms can be laid side by side in a space of one centimeter. In particular, the radius of the argon atom is 1.5×10^{-8} cm. The electrons around the atom neutralize the positive charge of the proton and the whole configuration has a neutral charge. The exact location of the electrons, sometimes referred to as their orbits, determines the chemical and physical characteristic of the atom. Atoms combine to form molecules by the interaction of the electrons of one atom with those of the other atoms in the molecule.

The total amount of energy that an atom has, sometimes referred to as the energy level, depends upon the configuration of the electrons in the various possible orbits. When energy is added to the atom, the electrons can be made to change orbits. Energy in the form of atomic radiation is released when the electrons again return to their normal orbits. Ultraviolet, visible, and infrared light are examples of atomic radiation.

In nucleonics the concern is not with the behavior of the electrons around the atom or the molecular structure of matter. Nucleonics is concerned with the characteristic of the heavy central core of the atom, the nucleus of the atom.

The nuclear radius of the atom is very small compared to the radius of the atom. While the radius of the argon atom is 1.5×10^{-8} cm, the radius of the argon nucleus is

4.1×10^{-13} cm. The radius of the atom is, therefore, 40,000 times as large as the radius of the nucleus of the atom. It can be seen from this that matter has very much open space and that the space occupied by the nucleus and the electrons is actually only a very small fraction of what appears to be solid matter. The projected nuclear area of aluminum foil 1.0 mil thick is only one part in 10^4 of the actual area, for example. This means that if it were possible to produce a shadow of what is actually solid matter in the aluminum foil, there would be one black dot for every 10,000 equally sized spaces of light. It is not surprising, therefore, that it is possible to shoot high velocity particles of the size of the nucleus of the atom through a foil of aluminum without approaching the nuclei of the aluminum. Were all matter solid and were it to have the density of the nucleus of the atom, one cubic millimeter (approximately the volume of the head of a pin) would weigh one hundred thousand tons.

In order to develop a simple series of numbers that would describe the weight of the various nuclei, physicists have defined a new weight standard referred to as the atomic weight. This standard is based upon the carbon atom composed of six protons, six neutrons, and six electrons. This carbon atom, abbreviated by the symbol ${}_6C^{12}$, is defined to have an atomic weight, in grams, of exactly 12.00000. If it were possible to assemble 6.0427×10^{23} atoms of carbon-12, the total weight would be 12.00000 grams. This quantity is referred to as atomic weight. Thus, the atomic weight of an atom is the weight of 6.0427×10^{23} atoms, and molecular weight is the weight of 6.0427×10^{23} molecules, both expressed in grams. It has been established further that this number of atoms or molecules of a gas, regardless of how complex they are, will occupy exactly 22.4 liters at zero degree centigrade and at a pressure of 76 mm Hg (mercury).

On the scale where the carbon atom ${}_6C^{12}$ is 12.00000, the mass of the hydrogen atom ${}_1H^1$ is 1.007825; the mass of the proton, the nucleus of the hydrogen atom, is 1.007276. On this same scale, the mass of the electron is .000549.

The nuclei of all atoms can be formed by combining specific numbers of neutrons and protons. Starting with hydrogen with its single proton, one addititional proton is added to each element through the 92 elements until uranium is reached, which has a total of 92 protons.

The number of neutrons in the nuclei of the various elements is not as simple. To the first approximation there are approximately as many neutrons as protons in a nucleus. For the nucleus of atoms having forty and more protons, however, the number of neutrons begins to exceed the number of protons in a nucleus. There are, in addition, "magic numbers" (2, 8, 14, 20, 28, 50, 82, and 126) that relate to the number of neutrons or protons in the nucleus of an atom. A nuclide containing one of these numbers of neutrons or protons is more stable than other nuclides.

A second complication is the fact that while in certain nuclei a single number of neutrons fits into the nucleus of the atom, in others a varying number of neutrons are permitted. For instance, gold with a total of 79 protons and 118 neutrons is the only kind found in nature. Mercury, on the other hand, with one more proton or a total of 80 protons, is found in nature with the following number of neutrons: 116, 118, 119, 120, 121, 122, and 124. No one has yet suggested a plausible reason for this complex behavior of the nucleus of the atom.

It is easily possible to determine the number of neutrons and protons in an atom from the symbols used by the physicist to describe atoms. For instance, gold is described by the symbol ${}_{79}Au^{197}$. The subscript 79 indicates that there are 79 protons present and that the gold atom carries an electrical charge of +79 units, where each unit of charge has the same magnitude as the electron. The 197 indicates that the total number of protons and neutrons is 197. By substracting the 79 protons from the total of 197, we arrive at the number of neutrons in the nucleus. The subscript that denotes the number of protons in the nucleus is called the atomic number and is given the symbol Z. The superscript is the total number of particles in the nucleus, or the mass number, and is given the symbol A.

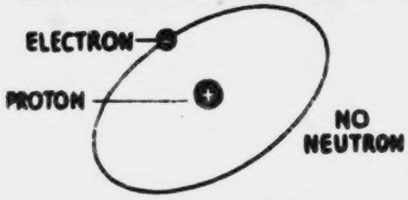
FAMILY *of* ATOMS

HYDROGEN ATOMS CAN HAVE SEVERAL FORMS

THESE ARE ISOTOPES

All Hydrogen Atoms Have One Proton

NATURAL OCCURRING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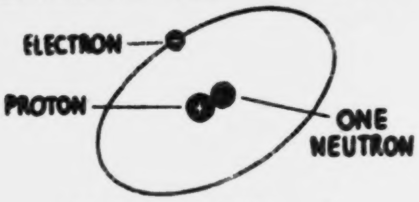
PROTON
NO NEUTRON

HYDROGEN 1
STABLE

NATURAL OCCURRING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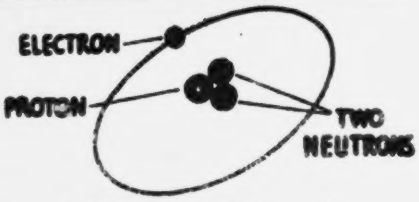
HYDROGEN 2
STABLE

MAN-MADE

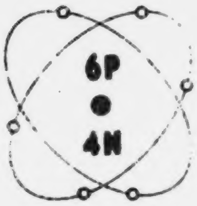

ELECTRON
PROTON
TWO NEUTRONS

HYDROGEN 3
RADIOACTIVE

WHAT ARE ISOTOPES

ISOTOPES ARE ATOMS OF AN ELEMENT DISTINGUISHABLE BY THEIR WEIGHT

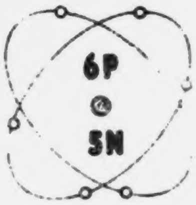
CARBON 10



MAN-MADE

RADIOACTIVE

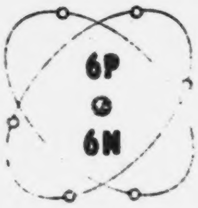
CARBON 11



MAN-MADE

RADIOACTIVE

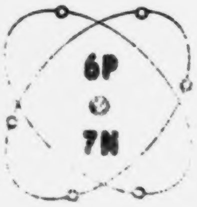
CARBON 12



OCCURS IN NATURE

STABLE

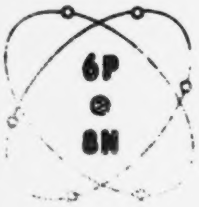
CARBON 13



OCCURS IN NATURE

STABLE

CARBON 14



MAN-MADE

RADIOACTIVE

The charge of the nucleus is always an exact integer but the masses of the nucleus are not integer numbers. Only carbon by definition has a nuclear mass of 12.00000 and all of the rest of the atoms have masses that are odd numbers. For instance, the mass of the hydrogen atom, while it is written as $_1H^1$, actually has a mass of 1.007825; the mass of the neutron, while it is written $_0n^1$, is 1.008665; and the electron, $_{-1}e^0$ has a mass of .000549. Later it will be seen that the fractional masses account for the energy that can be extracted from the atom.

QUESTIONS

1. What two items must be given in order to record a physical measurement?
2. In your own words, define mass, length, and time.
3. Why is it necessary to define the magnitude of primary standards of measurements?
4. From the definition of a yard, how many centimeters are there in one inch?
5. What two factors determine the length of time when the sun is at the zenith on two consecutive days?
6. Why is this time not a constant?
7. An electron moves a distance of 5 cm with a velocity of 3×10^9 cm/second. How long does it take?
8. Two electrons are separated by a distance of 3×10^{-7} cm. Calculate the repulsion force in dynes.
9. Name three other forms of energy.
10. If there are 6.06×10^{23} molecules of hydrogen (H_2) in one molecular weight, how many atoms of hydrogen are there in 1 cm^3?
11. How many atoms of hydrogen, carbon, and oxygen are there in one molecular weight of H_2CO_3?
12. A Coulomb is equal to one ampere flowing for one second. What is the total mass of the electrons in a Coulomb?
13. A liter contains 1000 cm^3. Calculate the mass of 1 cm^3 of helium gas at 1 atm and 0° C.
14. Name four transuranic elements (elements with atomic number larger than 92).
15. On a scale where the argon nucleus has a radius equal to that of a tennis ball, or approximately two inches, what would be the radius of the argon atom in feet?
16. Determine the number of neutrons and protons in $_{47}Ag^{107}$.

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2 natural radioactivity and atomic energy

PLAN OF INSTRUCTION

OBJECTIVE

1. To study the rays produced by radioactivity.
2. To briefly introduce natural radioactivity.
3. To outline the half-life of natural radioactive elements and introduce the concept of daughter products.
4. To study the alpha, beta, and gamma rays produced by natural radioactive substances.
5. To study the source of energy in radioactive decay products.

INTRODUCTION

1. Review the composition of the nucleus of the atom.
2. Review the masses of the elements as given in the appendix with emphasis upon the fact that the masses do not increase by integers even though the composition of the nucleus increases by an integer nucleon.
3. Introduce the concept of nuclear particles and the nomenclature of alpha rays, proton beams, and beta particles.

TEACHING PLAN

1. Introduce the concept that not all atoms are stable because they have an excess or a scarcity of neutrons in the nucleus of the atom.
2. Describe the force that must exist in the nucleus of an atom to hold the protons and neutrons together in the extremely small volume in which they are confined.
3. Introduce the forces involved in nuclear reactions.
4. Discuss the binding energy of nuclides and how it affects the formation of the atoms.
5. Diagram the uranium atom ${}_{92}U^{238}$ and draw a diagram of the atom showing the total number of neutrons and protons in the nucleus.
6. Define radioactivity as the spontaneous disintegration of one or more atoms and emphasize the fact that disintegration of any particular atom is a problematical occurrence.
7. Correlate the rate at which nuclei disintegrate with the half-life of the element and define half-life.
8. Write the disintegration sequence for ${}_{92}U^{238}$ on the board, indicating the emitted particle, the half-life, and the daughter product.

9. **Discuss the energy with which the radioactive particles are ejected from the nucleus of the atom.**

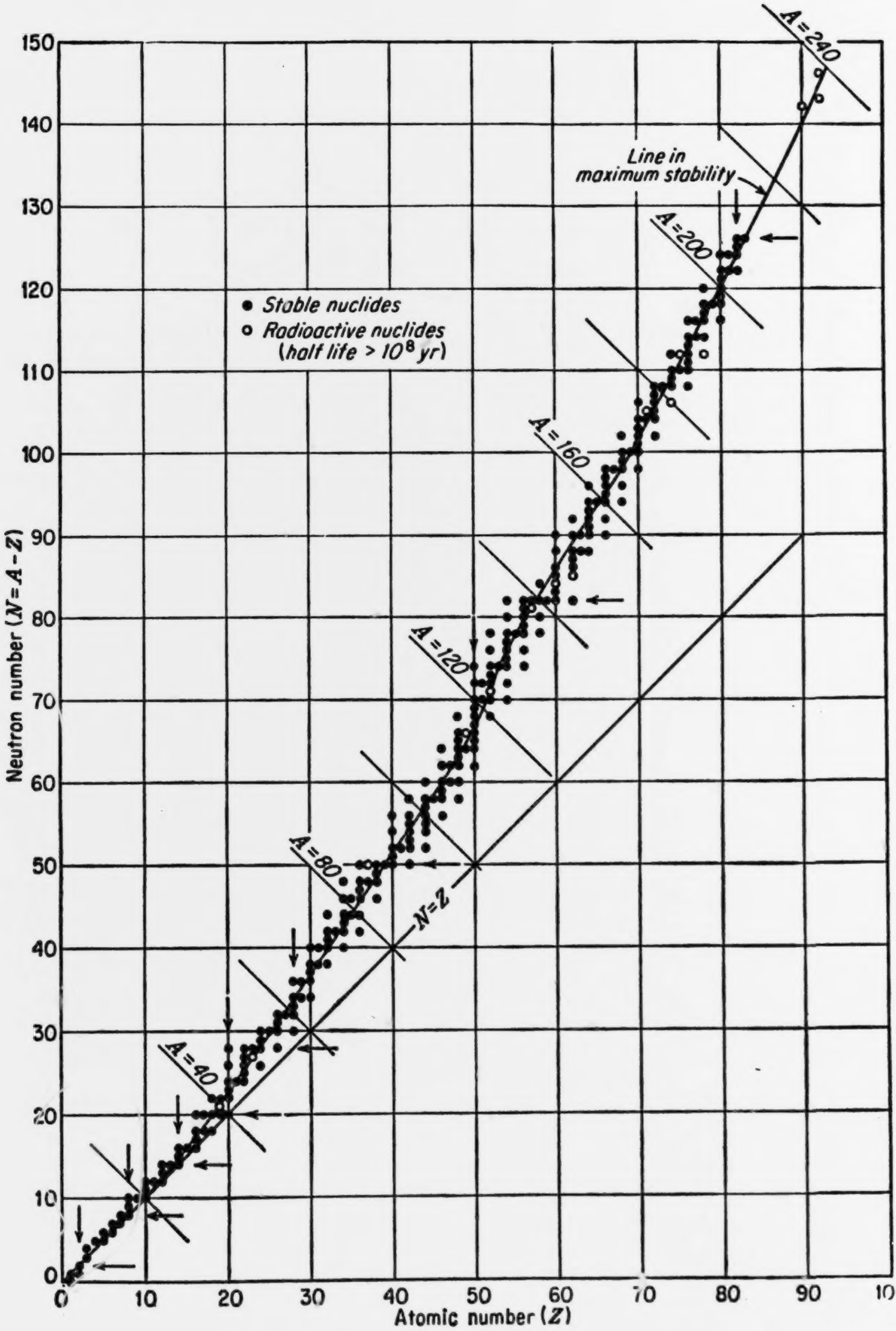


Fig. 2-1. Chart of the stable nuclides (From Nucleonics Fundamentals by D. B. Hoisington. Copyright 1959. McGraw-Hill Book Company, Inc., New York. Used by permission.)

10. Introduce Einstein's mass in energy formula, Energy = Mc^2, where M is the annihilated mass in grams, c is the velocity of light in centimeters per second, and energy is in ergs.

11. Discuss the production of gamma rays.

12. Mention the existence of radioactive elements other than those with atomic numbers beyond that of lead.

APPARATUS

None required.

RESOURCE MATERIAL

If we put together neutrons and protons at random to form nuclei, most of these combinations would be unstable and would not remain in combination. Some of the nuclei would spontaneously break into two or more fragments and would emit a ray called a gamma ray (which is identical to an X ray), the nucleus of a helium particle, a negative electron, a positive electron, a neutron, or a proton. Such unstable nuclei are called radioactive. Figure 2-1 gives a pictorial display of the atoms that are stable as a function of their atomic number Z and the number of neutrons N. In general, when the nucleus of an atom has an excess number of neutrons, it will be a negatron emitter and will emit an electron. When the nucleus of an atom has less than the stable number of neutrons, it will be a positron emitter or will capture electrons. Certain other nuclei, found generally among the very heaviest of elements, emit alpha particles, the nuclei of the helium atom. While this is generally true for atoms heavier than lead, a few instances of alpha emitters are found in nature.

Table 2-1
SOME NUCLEAR TERMS

Word	Definition	Examples
Nuclide	A nuclear species	
Radionuclide	A radioactive nuclide	
Isotope	One of several nuclides with the same proton number	Ca^{40}, Ca^{42}
Isotone	One of several nuclides with the same neutron number	Ca^{40}, K^{39}
Isobar	One of several nuclides with the same mass number	Ca^{40}, A^{40}
Isodiaphere	One of several nuclides with the same difference between neutron and proton numbers	Ca^{40}, K^{38}
Isomer	One of two nuclides with the same numbers of neutrons and protons but capable of existing, for a measurable time, in different energy levels	
Nucleon	A proton or a neutron	

The nucleus of an atom can exist with varying numbers of neutrons. Some combinations of neutrons and protons are found in nature and are stable. Other combinations of neutrons with the same number of protons are found to be unstable.

Nuclides with the same number of protons but with varying numbers of neutrons are called isotopes. The stable ones are referred to as stable isotopes and the unstable ones are referred to as radioactive isotopes. Over 280 stable nuclei are known to exist but well over 1,000 radioactive nuclei have been studied and cataloged.

The study of nucleonics is a study of the behavior of the unstable isotopes of the various elements and the reactions that take place when the radioactive elements undergo one of the many types of disintegration.

When charges carried by the elementary particles are far apart, the Coulomb forces react on the particles in exactly the same manner as they do with charges on large objects such as pith balls, sheets of paper, and hair. The formula for Coulomb forces shows that the forces increase with the inverse of the square of the distance between the particles. Thus, two positive charges, such as two protons, would experience a repulsion force that would become infinitely large as the protons are brought closer and closer together. In fact, this law would indicate that some millions of tons of force are required to squeeze two protons into the space they occupy in the nucleus. The Coulomb force equation does not hold when particles approach each other closer than 5×10^{-13} cm. At this point, an entirely different concept of forces and energy must be adopted; this is referred to as the binding energy of the nucleus of the atom. When a positively charged particle, a proton, for example, approaches the positive nucleus of the atom, it is strongly repulsed until it approaches within 5×10^{-13} cm. As the separation is decreased to approximately 3×10^{-13} cm, there is neither attraction nor repulsion forces between the two particles. If the proton approaches closer, there is a sudden increase in attraction force and the proton is captured by the nucleus of the atom.

A neutron, on the other hand, experiences no repulsion because it has a zero charge. It experiences an attraction when it reaches approximately 6×10^{-13} cm from the positively charged nucleus. At that point, the attraction force continues to increase until the neutron is captured by the nucleus of the atom.

The phenomenon of attraction when particles approach each other this closely is referred to by the term binding energy. The binding energy of a nuclide is defined as the amount of energy released upon the formation of the nuclide from neutrons and protium ($_1H^1$) atoms. In other words, it is the amount of energy that is required to break the nuclide into its component parts. Since the energy is released upon formation of the nuclide, the nuclide must stick together until this energy is somehow supplied to the nuclide. Only then is it able to separate into component parts. In a complex nuclide only one nucleon breaks away from the nuclide, leaving a comparatively large nucleus behind. In comparing nuclides, it is most useful to compare the binding energy present in nucleons, i.e., the total binding energy divided by the combined number of neutrons and protons in the nucleus. This is the average energy required to move a single nucleon or protium atom. The average binding energy of the nucleon is relatively constant and has a value between 7 Mev/nucleon to 8 Mev/nucleon, where Mev is the energy of one electron accelerated by a voltage of one million volts. Figure 2-2 gives the average binding energy as a function of the atomic mass.

Nuclides with small mass numbers have the smallest binding energy. As the mass numbers increase to 60, the binding energy reaches a maximum and thereafter decreases as the mass numbers increase. It can be seen, therefore, that if nuclides with small mass numbers approach close enough together so that attractive forces come into play, the nuclides will combine. The result is that they produce a nuclide of greater mass and more binding energy. This process releases energy and is referred to as nuclear fusion. Similarly, atoms with larger mass numbers can be caused to separate apart artificially or spontaneously, resulting in a nuclide with greater binding energy. This process again results in a release of energy from the system, and this process is known as nuclear fission. Energy released in these two processes is referred to as atomic energy; it is this energy that has been harnessed by man for the production of many devices.

The uranium atom ${}_{92}U^{238}$ is one of the heavier radioactive atoms. This atom forms one of a series of atoms that are unstable and disintegrate to form other atoms. The ${}_{92}U^{238}$ atom has a nucleus that consists of 92 protons and 146 neutrons and in its normal state has 92 electrons revolving in various orbits around the atom. The nuclear properties of the atom, however, are determined entirely and only by the particles in the nucleus of the atom. Figure 2-3 is a diagram showing the nuclear configuration of the atom that indicates the presence of the neutrons and protons.

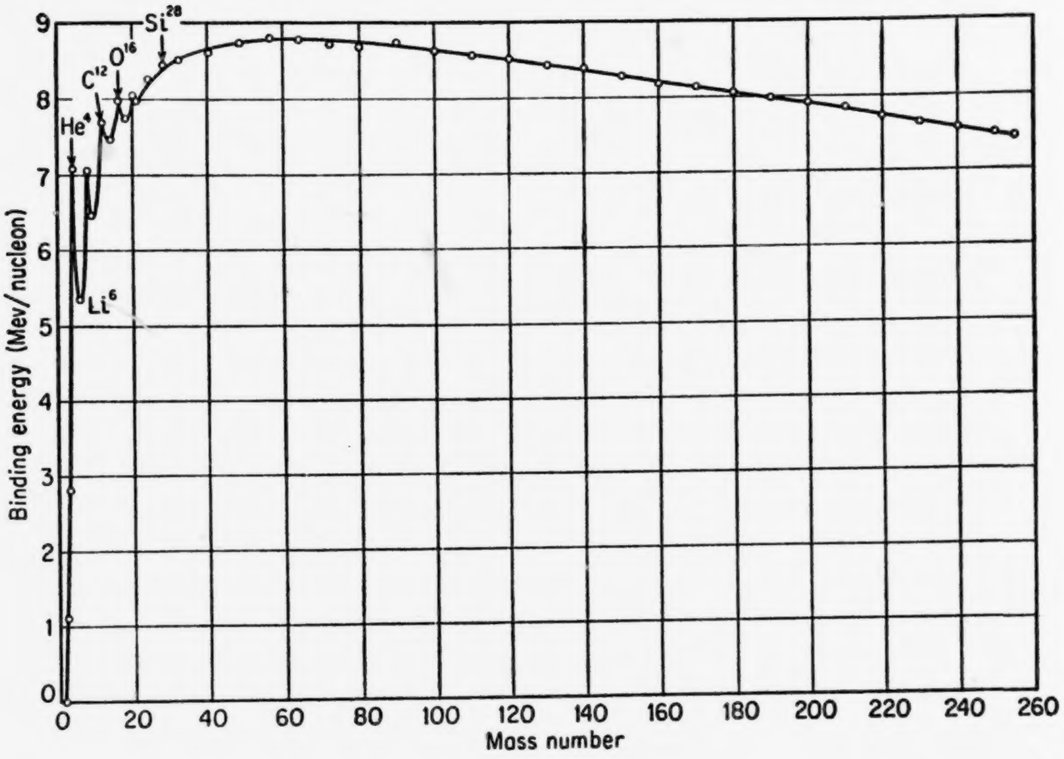


Fig. 2-2. Binding energy of the nuclides (From Nucleonics Fundamentals by D. B. Hoisington. Copyright 1959. McGraw-Hill Book Company, Inc., New York. Used by permission.)

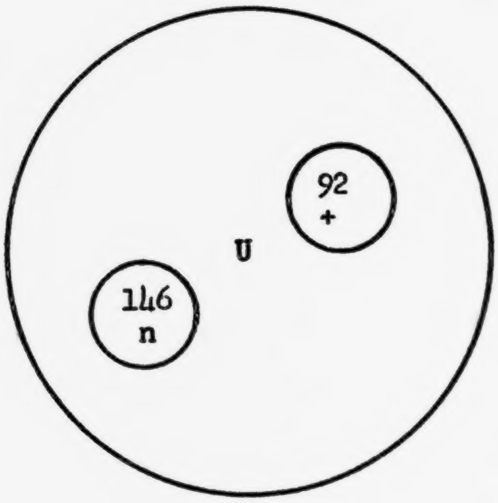
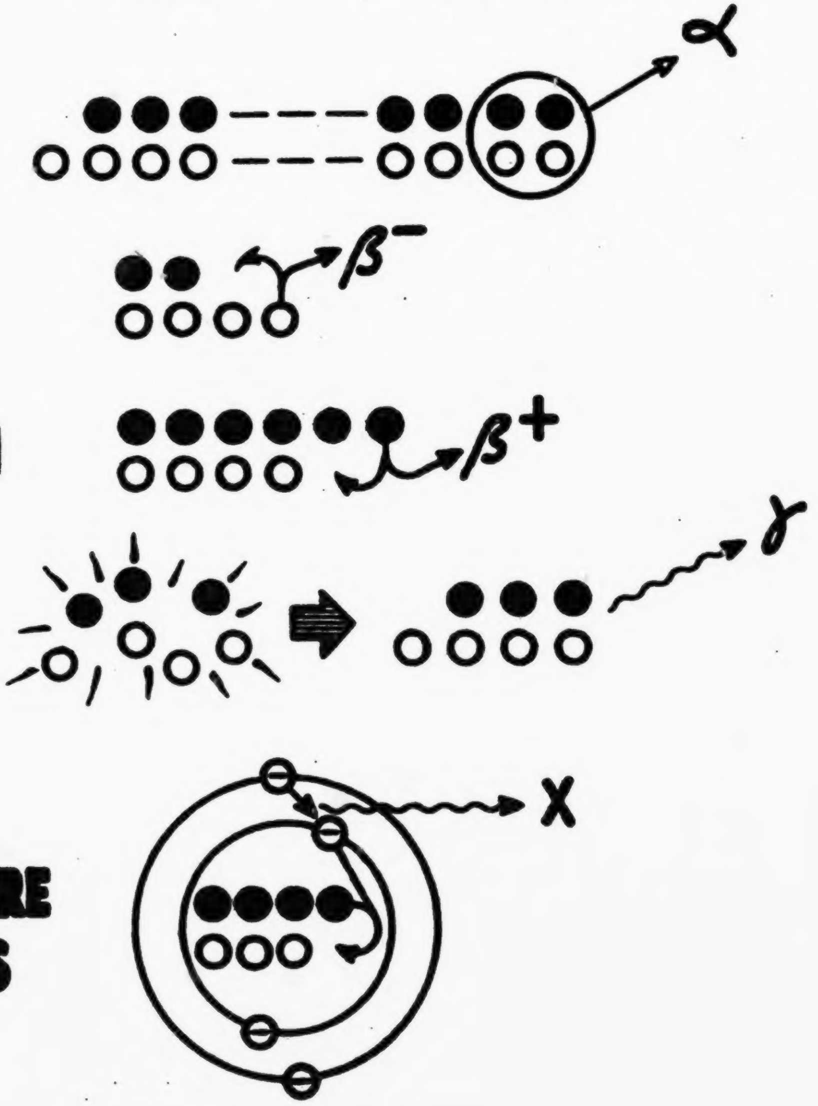


Fig. 2-3. The uranium nucleus with its 92 protons and 146 neutrons

Radioactivity is the spontaneous disintegration of the nucleus of an atom. This phenomenon is present in many atoms, particularly those atoms that are heavier than lead. A few of

MECHANISMS OF RADIATION

● PROTON ○ NEUTRON



ALPHA

BETA

POSITRON

GAMMA

K-CAPTURE
X-RAYS

the lighter elements are likewise radioactive, but all of the atoms beyond lead are radioactive. In addition to nuclei that are naturally radioactive, it is possible to use artificial means to create atoms that are radioactive.

Naturally radioactive elements emit one of two primary particles, an alpha particle or a beta particle, and will usually emit a gamma ray at the same time. The alpha particle is the nucleus of the helium atom ${}_2He^4$, carries two positive charges, and has a mass of 4. The beta particle is an electron emitted from the nucleus of the atom and is designated by ${}_{-1}e^0$. In both of the above disintegrations, the charge is in exact units of the charge of the electron, but the masses indicated in the symbol are inexact numbers. Thus, the mass of the electron is not quite zero, but .000549; the mass of the helium nucleus is not exactly 4, but rather 4.002600.

The gamma ray is an electromagnetic form of radiation with characteristics similar to light and X ray. It travels in a straight line, is unaffected by an electric field or a magnetic field, and penetrates through matter similar to the way in which X rays penetrate through matter.

The disintegration of a radioactive nucleus is based purely on probability. That is, for a given atom in the many atoms of a radioactive sample, it is impossible to predict when it will disintegrate by the emission of an alpha particle or a beta particle. However, after a period referred to as the half-life of the element, one-half of the nuclei will have undergone disintegration. The half-lives of elements vary from that of thorium ${}_{90}Th^{132}$, which is 1.39×10^{10} years, to that of polonium ${}_{84}Po^{214}$, which has a half-life of approximately 0.0001 second.

Elements that have a very long half-life obviously undergo disintegration very slowly while elements that have a very short half-life undergo disintegration very rapidly. It is perfectly safe to handle an element like ${}_{90}Th^{132}$ with its long half-life, because in such an element only one-half of the total nuclei undergo a radioactive disintegration with the emission of rays in 10 billion years. It is possible to write a simple formula that describes the rate of disintegration in terms of the disintegration constant. The number of atoms that undergo a radioactive decay in a period of time dt is given by the equation $dN = \lambda Ndt$ where dN denotes the number of atoms that undergo radioactive decay. If the half-life of the element is longer than an hour, the number of atoms that decay in one second can be given by

$$\text{atoms/sec} = N\lambda$$

where N is equal to the total number of atoms in the sample.

Tables 2-2, 2-3, and 2-4 give the radioactive species, nuclides, type of disintegration, half-life, and disintegration constant for most of the naturally radioactive elements. The number of atoms in any sample can be determined by weighing the sample in grams and applying the following formula

$$N = \frac{\text{mass of sample in grams}}{\text{atomic weight of nuclide}} \times 6.0427 \times 10^{23}$$

The total number of radioactive decays per second is then calculated by multiplying the number of atoms in the sample by the disintegration constant for the particular nuclide.

When the disintegration constant is not given but when the half-life is known, the former can be obtained by

$$\lambda = 0.693/T$$

where T is the half-life of the radioactive element.

Table 2-2
THE URANIUM SERIES

Radioactive species	Nuclide	Type of disintegration	Half-life	Disintegration constant (sec^{-1})	Particle energy (Mev)
Uranium I (UI)	${}_{92}U^{238}$	α	4.50×10^{9}y	4.88×10^{-18}	4.20
Uranium X_1 (UX_1)	${}_{90}Th^{234}$	β	24.1 d	3.33×10^{-7}	0.20
Uranium X_2 (UX_2)	${}_{91}Pa^{234}$	β	1.18 m	9.77×10^{-3}	2.32
Uranium Z (UZ)	${}_{91}Pa^{234}$	β	6.7 h	2.88×10^{-5}	1.2
Uranium II (UII)	${}_{92}U^{234}$	α	2.50×10^{5}y	8.80×10^{-14}	4.763
Ionium (Io)	${}_{90}Th^{230}$	α	8.0×10^{4}y	2.75×10^{-13}	4.68 m
Radium (Ra)	${}_{88}Ra^{226}$	α	1620 y	1.36×10^{-11}	4.777 m
Ra Emanation (Rn)	${}_{86}Em^{222}$	α	3.82 d	2.10×10^{-6}	5.486
Radium A (RaA)	${}_{84}Po^{218}$	α, β	3.05 m	3.78×10^{-3}	α:5.998 β:?
Radium B (RaB)	${}_{82}Pb^{214}$	β	26.8 m	4.31×10^{-4}	0.7
Astatine-218 (At^{218})	${}_{85}At^{218}$	α	1.5-2.0 s	0.4	6.63
Radium C (RaC)	${}_{83}Bi^{214}$	α, β	19.7 m	5.86×10^{-4}	α:5.51 m β:3.17
Radium C' (RaC')	${}_{84}Po^{214}$	α	1.64×10^{-4}s	4.23×10^{3}	7.680
Radium C" (RaC")	${}_{81}Tl^{210}$	β	1.32 m	8.75×10^{-4}	1.9
Radium D (RaD)	${}_{82}Pb^{210}$	β	22 y	1.00×10^{-9}	0.018
Radium E (RaE)	${}_{83}Bi^{210}$	β	5.0 d	1.60×10^{-6}	1.17
Radium F (RaF)	${}_{84}Po^{210}$	α	138.3 d	5.80×10^{-8}	5.300
Thallium-206 (Tl^{206})	${}_{81}Tl^{206}$	β	4.2 m	2.75×10^{-3}	1.51
Radium G (RaG)	${}_{82}Pb^{206}$	Stable			

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Table 2-3
THE ACTINIUM SERIES

Radioactive species	Nuclide	Type of disintegration	Half-life	Disintegration constant (sec^{-1})	Particle energy (Mev)
Actinouranium (AcU)	${}_{92}U^{235}$	α	7.10×10^{8}y	3.09×10^{-17}	4.58 m
Uranium Y (UY)	${}_{90}Th^{231}$	β	24.6 h	7.82×10^{-6}	0.30
Protoactinium (Pa)	${}_{91}Pa^{231}$	α	3.43×10^{4}y	6.40×10^{-13}	5.042 m
Actinium (Ac)	${}_{89}Ac^{227}$	α, β	22.0 y	1.00×10^{-9}	α:4.94 β:0.04
Radioactinium (RdAc)	${}_{90}Th^{227}$	α	18.6 d	4.31×10^{-7}	6.05 m
Actinium K (AcK)	${}_{87}Fr^{223}$	β	21 m	5.50×10^{-4}	1.2
Actinium X (AcX)	${}_{88}Ra^{223}$	α	11.2 d	7.16×10^{-7}	5.75 m
Ac Emanation (an)	${}_{86}Em^{219}$	α	3.92 s	0.177	6.824 m
Actinium A (AcA)	${}_{84}Po^{215}$	α, β	1.83×10^{-3}s	3.79×10^{2}	α:7.365
Actinium B (AcB)	${}_{82}Pb^{211}$	β	36.1 m	3.20×10^{-4}	1.39
Astatine-215 (At^{215})	${}_{85}At^{215}$	α	10^{-4}s	7×10^{3}	8.00
Actinium C (AcC)	${}_{83}Bi^{211}$	α, β	2.16 m	5.25×10^{-3}	α:6.621 m
Actinium C' (AcC')	${}_{84}Po^{211}$	α	0.52 s	1.33	7.434 m
Actinium C" (AcC")	${}_{81}Tl^{207}$	β	4.79 m	2.41×10^{-3}	1.44
Actinium D (AcD)	${}_{82}Pb^{207}$	Stable			

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There are three naturally radioactive series and they are in the elements heavier than lead. The series start with uranium $_{92}U^{238}$, uranium $_{92}U^{235}$, called the actinium series, and thorium $_{90}Th^{232}$. By referring to Tables 2-2, 2-3, and 2-4, it will be noted that the stable end products of the series are lead $_{82}Pb^{206}$, $_{82}Pb^{207}$, and $_{82}Pb^{208}$.

Table 2-4
THE THORIUM SERIES

Radioactive species	Nuclide	Type of disintegration	Half-life	Disintegration constant (sec^{-1})	Particle energy (Mev)
Thorium (Th)	$_{90}Th^{232}$	α	1.39×10^{10}y	1.58×10^{-18}	3.98
Mesothorium 1 (MsTh1)	$_{88}Ra^{228}$	β	6.7 y	3.28×10^{-9}	0.04
Mesothorium 2 (MsTh2)	$_{89}Ac^{228}$	β	6.13 h	3.14×10^{-5}	2.18
Radiothorium (RdTh)	$_{90}Th^{228}$	α	1.90 y	1.16×10^{-8}	5.423 m
Thorium X (ThX)	$_{88}Ra^{224}$	α	3.64 d	2.20×10^{-6}	5.681 m
Th Emanation (Tn)	$_{86}Em^{220}$	α	54.5 s	1.27×10^{-2}	6.282
Thorium A (ThA)	$_{84}Po^{216}$	α, β	0.16 s	4.33	6.774
Thorium B (ThB)	$_{82}Pb^{212}$	β	10.6 h	1.82×10^{-5}	0.58
Astatine-216 (At^{216})	$_{85}At^{216}$	α	3×10^{-4}s	2.3×10^{3}	7.79
Thorium C (ThC)	$_{83}Bi^{212}$	α, β	47 m	2.46×10^{-4}	α:6.086 m β:2.25
Thorium C' (ThC')	$_{84}Po^{212}$	α	3.0×10^{-7}s	2.31×10^{6}	8.776
Thorium C" (ThC")	$_{81}Tl^{208}$	β	2.1 m	3.73×10^{-3}	1.79
Thorium D (ThD)	$_{82}Pb^{208}$	Stable			

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The radioactive nuclides undergo a complex disintegration by emitting an alpha or beta particle in a sequence that is given in the table and diagramed in Fig. 2-4. Referring to Fig. 2-4 and the uranium-238 series, it will be noted that when an alpha particle is emitted both the atomic number and the number of neutrons decrease by two; whereas, when a beta particle is emitted, the number of neutrons is decreased by one and the atomic number is increased by one unit.

The particles that are emitted from the nuclide are emitted with varying velocities. The energy of the emitted particle is usually given in terms of million electron volts. A million electron volts means that the particle is moving as rapidly as it would if it had the charge of one electron and were accelerated by one million volts. The energy indicated in Tables 2-2, 2-3, and 2-4 is the energy of the particles in terms of million electron volts. In those cases where an alpha particle may have several energy values, the greatest value is listed and is denoted by "m."

The energy in million electron volts is related to the distance the particle can travel in air, referred to as the range. The range is a complex function of the energy, but a few examples are useful. An alpha particle with 4.2 Mev energy has a range in air of 2.7 cm while an alpha particle with 7.68 Mev energy has a range of 6.97 cm. The range of beta particles can be estimated by the fact that the range is approximately one hundred times as large for the same energy level as the range of the alpha particle.

The source of energy that causes the particle to be expelled from the nucleus of a radioactive nuclide can be calculated by applying Einstein's mass-to-energy equation to the mass defect between the parent element, the daughter element, and the particle emitted. The annihilated energy of one mass unit can be calculated and is found to be 931 Mev. This can be applied to the first disintegration of the uranium series as follows:

$_{92}U^{238}$ equals 238.0508

$$\begin{array}{lr} _{90}Th^{234} & 234.0436 \\ _{2}He^{4} & 4.0026 \\ \hline & 238.0462 \end{array} \qquad \begin{array}{lr} & 238.0462 \\ \text{Mass to energy} & .0046 \\ \hline \text{Original mass} & 238.0508 \end{array}$$

Thus, energy = (931) (.0046) = 4.1 Mev. This calculated value is in close agreement with the published value of 4.2 Mev.

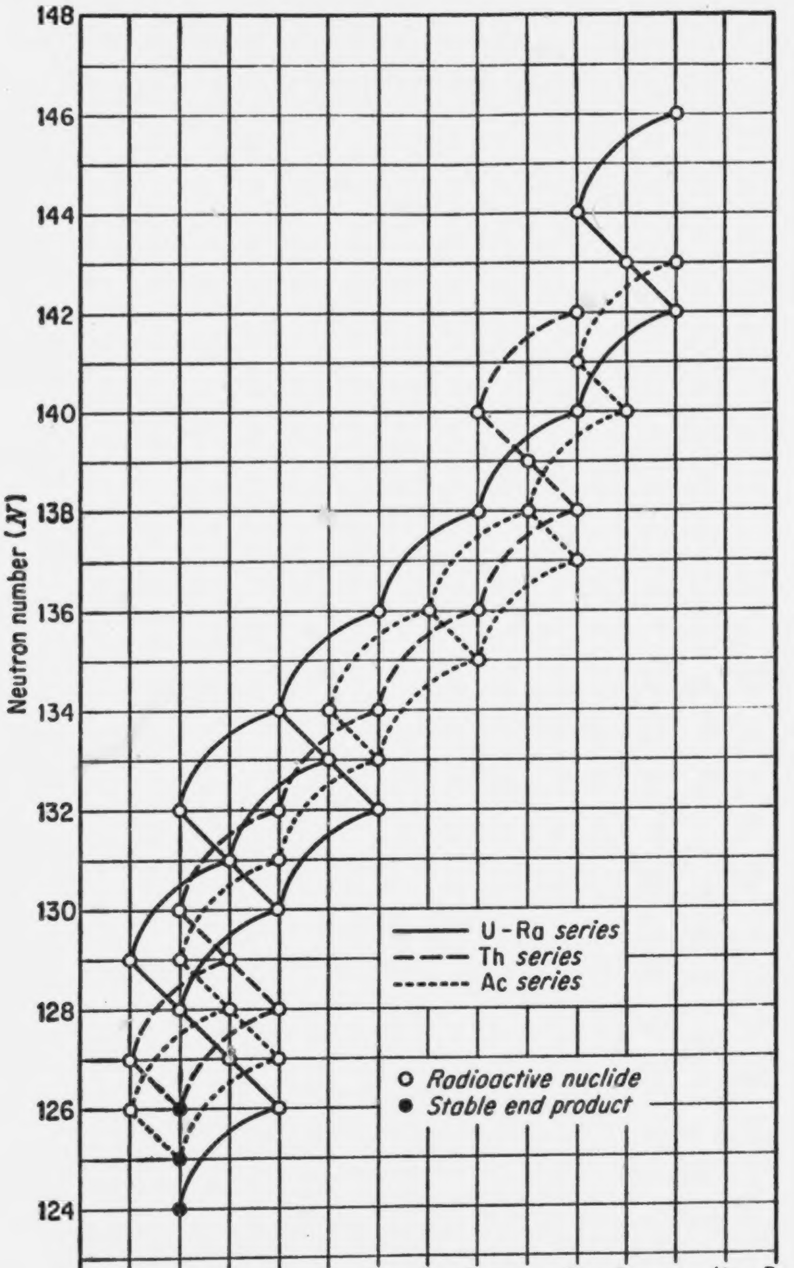
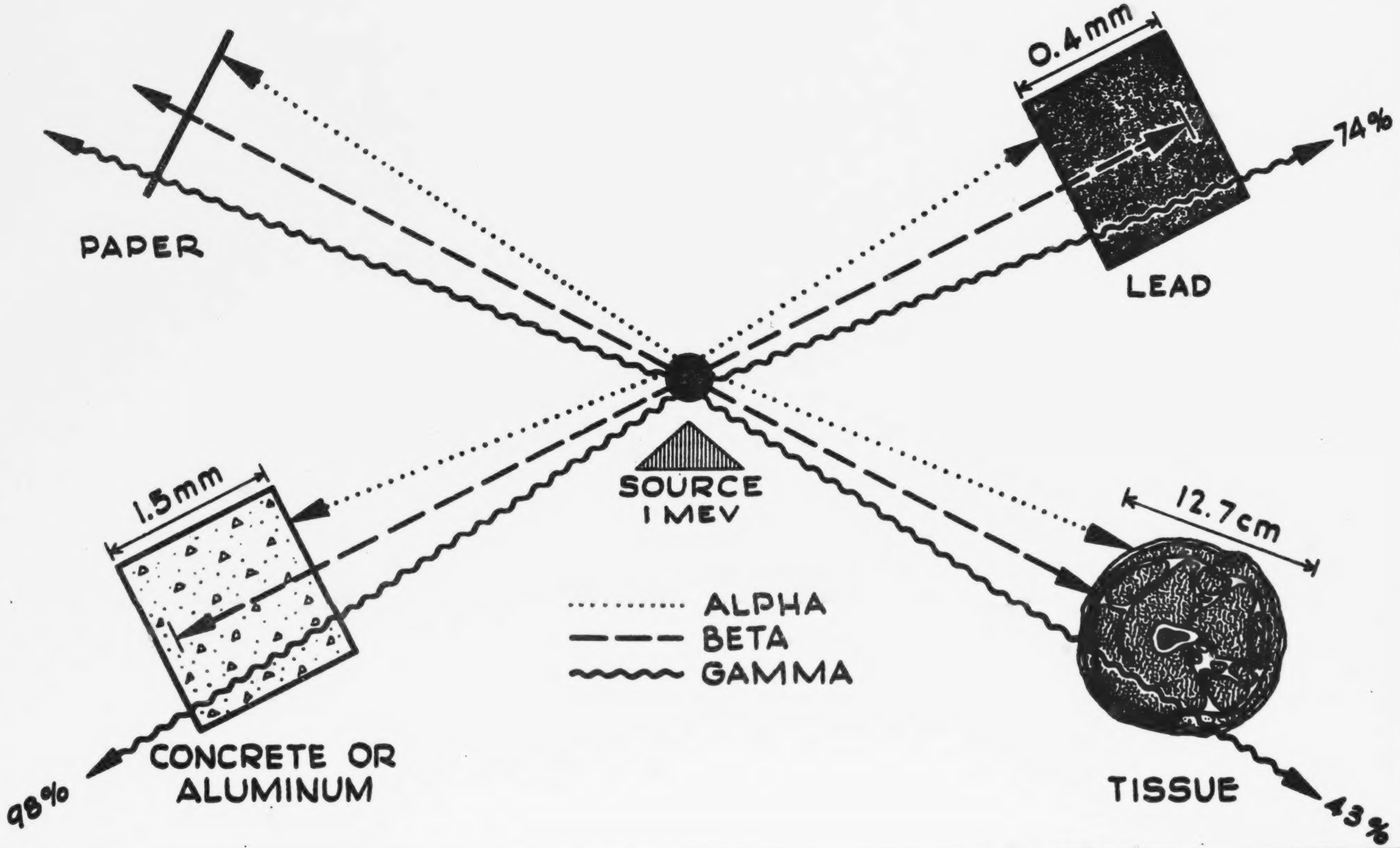


Fig. 2-4. The natural radioactive series (From Nucleonics Fundamentals by D. B. Hoisington. Copyright 1959. McGraw-Hill Book Company, Inc., New York. Used by permission.)

Gamma rays are produced in many radioactive disintegrations. The energy of the resulting gamma rays varies extensively, and tables are not available that give the individual energies for each of the various nuclides. Gamma rays can be thought of as using up the residual bit of excess mass remaining after the alpha or beta particle has been emitted. The range of gamma particles is approximately one hundred times as great as the range of the beta particle and about ten thousand times as great as the range of an alpha particle. Thus, it can be seen that the range of a gamma ray in air may be as much as 50 thousand cm, or one-fourth of a mile. Furthermore, gamma rays will penetrate through a similarly large thickness of shielding material, and it is not unusual to find from one to two inches of lead shields employed to reduce the radiation due to gamma rays.

Radiation Absorption
IN VARIOUS MATERIALS


0.4 mm
74%
PAPER
LEAD
SOURCE
1 MEV
1.5mm
12.7 cm
ALPHA
BETA
GAMMA
98%
CONCRETE OR
ALUMINUM
TISSUE
43%

QUESTIONS

1. Describe in your own words: (a) the gamma ray, (b) alpha particle, (c) beta particle.
2. Calculate the force in dynes exerted on an alpha particle when it is 1 x 1^{-12} from the nucleus of a manganese atom ($Z = 25$).
3. Since the nucleus of the atom contains only protons and neutrons, describe what must happen when a beta particle (negative electron) is ejected from the nucleus.
4. What is an isobar?
5. What is the source of energy from the atom?
6. Define natural radioactivity.
7. Name ten atoms that are naturally radioactive.
8. In a sample whose activity is 10 μc, how many atoms undergo disintegration each second?
9. Find the disintegration constant for thorium-132, whose half-life is 1.39 x 10^{10} years, and for polonium-214, whose half-life is 0.0001 second.
10. Referring to Fig. 2-4, not all of the possible nuclides are connected by the three series shown. Does this indicate the presence of a fourth series?
11. Why is the gamma ray not deflected by an electric field or a magnetic field?
12. A positron and an electron can combine to produce a gamma ray. The energy of the gamma ray is equal to the annihilation energy of the mass of the electron plus proton. Calculate the energy of the resulting gamma ray.

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3 induced radioactivity and atomic energy

PLAN OF INSTRUCTION

OBJECTIVE

1. To study the effect of adding particles to the nucleus.
2. To briefly outline devices that can be used to accelerate particles for the purpose of bombarding the nucleus of atoms.
3. To study the production of induced radioactivity.
4. To calculate the energy in simple induced reactions.
5. To introduce neutron bombardment and sample reactions.
6. To study the use of charts similar to the General Electric "Chart of the Nuclides."

INTRODUCTION

1. Review the size of the nucleus and concept of open space in matter.
2. Review forces that repel a positively charged particle as it approaches the nucleus of an atom.
3. Review forces on charged particles that make it possible to accelerate a particle.
4. Review the concept of a magnetic field that causes a particle to change its direction but not its velocity.

TEACHING PLAN

1. Refer to Fig. 2-1 and show that addition on nucleons or the subtraction on nucleons brings the resulting nucleus into an unstable condition.
2. Discuss possible bombarding particles.
3. Introduce a direct voltage type machine to accelerate particles.
4. Describe the cyclotron.
5. Describe the linear accelerator.
6. Describe the betatron.
7. Discuss the effects of bombarding by alpha particles from naturally radioactive sources.
8. Discuss the effect of bombardment with beta particles or high velocity electrons and the production of X ray.
9. Describe the formation of a series of daughter elements ending in a stable nucleus.

10. Introduce the concept of recoil velocity as a function of the inverse of the masses of the disintegration fragments.

11. Point out that almost the entire energy of the reaction results in the formation of heat.

12. Introduce the concept of fusion and illustrate with the formation of helium from hydrogen.

13. Introduce the concept of fission and illustrate with ${}_{92}U^{235}$.

14. Calculate the energies in the above two reactions.

APPARATUS

None required.

RESOURCE MATERIAL

Figure 2-1 shows the relationship between the atoms as a function of the atomic number Z and the number of neutrons in the atom. It will be noted that for elements whose atomic mass is less than 40, the number of protons and neutrons are nearly the same. However, if the atomic mass increases beyond 40 or the atomic number beyond 20, the line of maximum stability in the nucleus of the atom bends upward and the nuclei of the stable atoms begin to have an excess number of neutrons. No simple explanation has been given for the relationships between neutrons and protons in a stable nucleus.

Any combination of neutrons and protons other than the stable ones indicated by the solid dot in Fig. 2-1 are unstable. In general, unstable elements with an excess of neutrons (or those found on the upper side of the line of maximum stability) are negatron emitters and emit beta particles. Nuclides that are unstable have a deficiency of neutrons (those found below the line) and are positive emitters. They emit either a proton, alpha particles, or capture an electron in order to approach the area of stability.

Any chart similar to Fig. 2-1 is not complete enough to give all of the desired information. A chart that is more complete is printed and distributed by the Knolls Atomic Power Laboratory of the General Electric Company and is referred to as the "Chart of the Nuclides." It is available without cost from Educational Relations, Department MWH, General Electric Company, Schenectady, New York. The chart enables students to read directly the type of radiation produced by each nuclide, the half-life of the nuclide, the energy of the radiating particle, and other pertinent information.

As discussed in Session 2, nuclear forces begin to act in a direction that will cause the bombarding particle to be attracted to the nucleus of the atom if the separation between the particles is less than 3×10^{13} cm. Prior to this time, a positive nucleus will repel a positive bombarding particle and, likewise, an electron will be repelled by the shells of electrons around the nucleus of the atom. In order for a particle to approach the nucleus of the atom closely enough so that it is attracted to and combines with the nucleus, it is necessary to accelerate the particle to a sufficiently high velocity so that it can overcome the repelling forces. Since the velocity of the particle having a small charge is very high for the same energy, it can be seen that a proton or the nucleus of a hydrogen atom achieves a very high velocity with low energy and would, therefore, be able to penetrate close enough to the nucleus to be absorbed by the nucleus. Deuteron, the nucleus of of heavy hydrogen ${}_{1}H^{2}$ (sometimes written as ${}_{1}D^{2}$), is a second choice. Alpha particles obtained either from natural radioactive sources or produced by accelerating the nucleus of the helium atom ${}_{2}He^{4}$ have been used extensively as bombarding particles.

The neutron, ${}_{0}n^{1}$, has no charge and, therefore, is not repelled by the charge on either the shells of the electrons or the nucleus itself. It can approach the nucleus of the atom with

ISOTOPES

(NUCLEAR SPECIES OR NUCLIDES)

TOTAL NUMBER IDENTIFIED ~ 1175

STABLE

NUMBER IDENTIFIED	~	275
NUMBER AVAILABLE IN CONCENTRATED FORM	~	190

RADIOACTIVE

NUMBER IDENTIFIED	~	900
NUMBER OCCURRING IN NATURE	~	50
NUMBER DISTRIBUTED FROM REACTOR	~	100

little or no velocity. Consequently, it is not strange that the neutron can readily combine with all forms of atoms.

Since, however, a fast neutron can add to the total energy of the nucleus, some distinction must be made for the velocity of neutrons and their probability of capture. Data relating to the resulting nucleus are divided between fast neutrons and slow neutrons, sometimes referred to as thermoneutrons.

The probability that a neutron will react with a particular nucleus may be expressed in terms of σ, the microscopic neutron cross section for the particular reaction. The value of σ is expressed as an area and is proportional to the probability that the reaction will take place. The larger the value of σ, the larger the nucleus "appears" to the neutron and the greater the probability of reaction. The microscopic cross section σ is usually given in barns, where a barn is 10^{-24} cm^2. The nuclear cross section for various reactions ranges from zero through millibarns (mb) to several million barns. It is interesting to compare these values with the physical cross-sectional area of the nuclei. The diameter of any nucleus of mass number A is given by

$$d=2.4A^{1/3} \times 10^{-13} \text{ cm.}$$

The physical cross-sectional areas of atomic nuclei, therefore, vary from 0.045 barns for hydrogen to 1.18 barns for uranium.

The capture cross section area is complicated further by the fact that the total cross section σ varies with the energy of the neutron. For instance, the cross section σ for indium varies from 30,000 barns to 10 barns for neutron energies that vary from 1 ev to 1 Mev. Cadmium, for example, is useful in an atomic power plant because it has a large total cross section for thermoneutrons, 20,800 barns. It attracts and absorbs neutrons at great distances from the cadmium nucleus because of its large cross section and because the resulting nuclide is in itself stable. Thus, the use of cadmium rods makes it possible to remove neutrons from the volume without increasing the radioactivity in the area.

The elementary particle that has the smallest chance of penetrating into the nucleus is the electron. Generally, the electron is deflected by the shells of electrons around the nucleus of the atom, and this results in energy that is liberated in the form of X rays. Electrons are captured, however, by the nucleus of the atom, and the capture of an electron produces the same effect as emitting a positive particle.

Since 1930, a large number of devices have been produced to accelerate particles to bombard the nucleus of the atom. In each case, the purpose has been to make a radioactive atom and to observe the reactions that would take place. The simplest machine is a direct-current, high-voltage unit that, in combination with a source of positively charged particles, attracts positively charged particles to the negative end of the device. In order to avoid collision with atoms in their path, positively charged particles are caused to travel down an evacuated tube. Upon reaching the negative end of the tube, they have acquired a velocity given by the equation

$$1/2Mv^2 = eE$$

where M is the mass of the particle in grams, v is the velocity in centimeters per second, e is charge on the particle in electrostatic volts, and E is the voltage drop in electrostatic volts.

A second device is the resonance accelerator, more commonly referred to as the cyclotron. Figure 3-1 shows the essential features of the cyclotron. It consists of a large magnetic field and evacuated chamber that houses two insulated electrodes, called "dees," that are excited by a powerful radio frequency transmitter. In addition, a source of ions is located at the center of the device. The positive ion is alternately attracted to the left then to the right dee and travels a circular path because of the magnetic field. The frequency of the alterations of the electrical field applies to the dees, and the magnetic field is adjusted until the charged particle completes a one-half rotation in exactly the time that it takes the electric voltage to reverse. Thus, the charged particle is positioned at the gap between the dees at the exact time that the voltage is at its maximum again. The energy acquired by the positive ion is equal to the voltage across the dees multiplied by the number of times the particle is accelerated across the gap multiplied by the charge on the particle. Thus, a proton with one positive charge attains an energy of 8,000,000 electron volts, or 8 Mev, if it makes 80 revolutions and the voltage across the dees is 50,000 volts. It is obvious that one of the chief advantages of the cyclotron is that an energy of 8,000,000 electron volts can be achieved with an alternating source voltage of 50,000 volts.

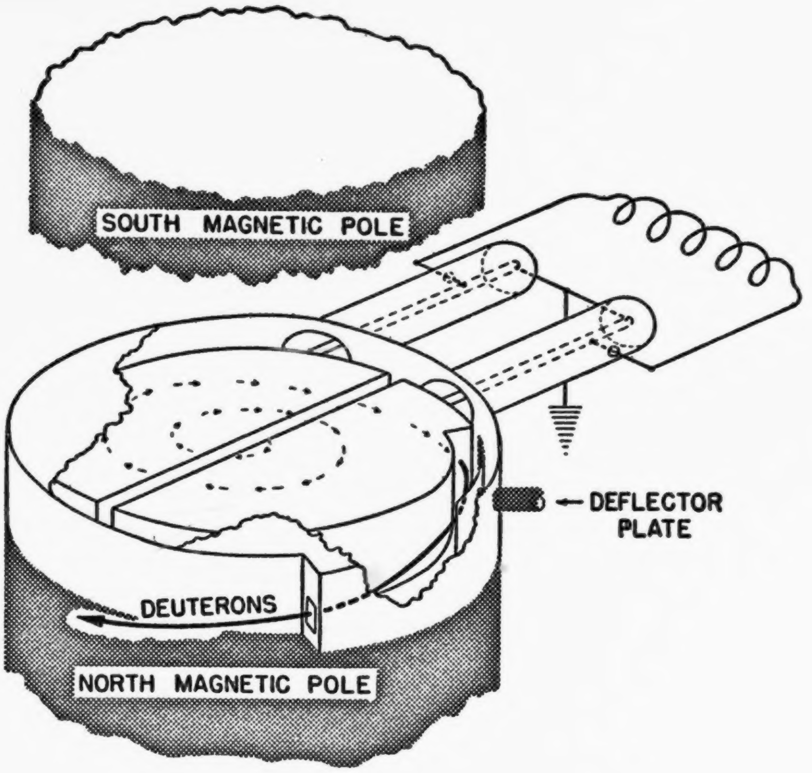

Fig. 3-1. Schematic view showing action of the cyclotron (From Radioactivity and Nuclear Physics by J. M. Cork. Copyright 1957. D. Van Nostrand Company, Inc., Princeton, N.J. Used by permission.)

A linear accelerator is a device with a series of very high frequency radar type tubes that are used to accelerate positively or negatively charged particles through an evacuated hollow tube. Voltages are applied to a series of hollow conductors, the length of which successively increases in such a manner that the charged particle reaches the gap between the next section at the exact time that the voltage is in such a direction to produce acceleration. Early models of this device were from 10 to 50 feet long and present designs have extended the length to one mile in a unit at Stanford University. The linear accelerator accelerates both electrons and light positive particles and has been successful using particles with masses as high as 20 to 30 atomic mass units.

The betatron is a device that is designed specifically to accelerate electrons. Similar to the cyclotron, the betatron has a magnetic field to keep the electron in a circular path, but the accelerating force is provided by an increase in the magnetic field.

Other bombarding devices are in common use in radiation laboratories. The bevatron, so named because it is capable of achieving energies in excess of a billion electron volts, or

Bev, likewise employs a varying magnetic field and produces a series of burst of high energy particles. Another device for bombarding the nucleus of atoms uses an alpha source from one of the naturally radioactive isotopes. Such sources are available by utilizing polonium $_{84}Po^{210}$, which emits alpha particles having a range of 3.9 cm in air and an energy of 5.4 Mev.

A simple reaction illustrating the phenomenon of bombarding a nucleus of the atom with an alpha particle is illustrated by the capture of an alpha particle by nitrogen and the ultimate disintegration of the resulting nucleon into oxygen:

$$_2He^4 + {}_7N^{14} = ({}_9F^{18}) = {}_8O^{17} + {}_1H^1$$

When the alpha particle with the charge of +2 and the mass 4 collides with the nitrogen nucleus with a charge of +7 and mass of 14, they form a single particle with a charge of +9 and a mass of 18. Since an atom with the nuclear charge of +9 would be expected to have all the chemical properties of fluorine, atomic number 9, the newly formed nucleus is labeled $_9F^{18}$.

An examination of the table of isotopes, however, shows that no such isotope exists in nature. This combination of neutrons and protons is unstable and disintegrates by discharging a proton, a particle of charge +1 and a mass of 1. This leaves behind a residual nucleus with a charge of +8 and a mass of 17, one of the stable isotopes of oxygen.

In like manner, beta particles are emitted from certain radioactive elements. These are high velocity electrons and can be produced with a high voltage accelerator, betatron, or linear accelerator. The effect in each of these cases is similar. When a beta particle or a high velocity electron interacts with an atom, the electron is rarely able to penetrate through the shells of electrons and reach the nucleus of the atom. More commonly, electrons are ejected from their shells and when this takes place in one of the innermost shells, X rays are produced. This type of radiation is particularly dangerous in that X rays, in a manner identical to gamma rays, penetrate through large sections of absorbing material and produce deep radiation burns. When the outer shells of the electrons are disturbed, infrared, visible, and ultra-violet light are produced.

In addition to producing a reaction that results in an instaneous disintegration from a new atom, it is possible to produce artificially radioactive elements by bombardment. One such reaction is the production of radioactive phosphorus. The reaction is as follows:

$$_2He^4 + {}_{13}Al^{27} = {}_{15}P^{30} + {}_0n^1$$

A newly created particle, with a charge of +15 and a mass of 30, is a phosphorus that is not stable. The radioactive phosphorus nuclei $_{15}P^{30}$ emits a positron, leaving behind a stable silicon atom of charge +14 and mass 30:

$$_{15}P^{30} = {}_{14}Si^{30} + {}_1e^0$$

The half-life of this activity is 2.5 minutes.

Other artificially produced reactions have varying half-lives. That of Carbon 14, for example, is approximately 5,600 years.

In many instances, induced radioactive nuclei undergo a series of disintegrations before becoming stable. This is particularly true of elements that are produced in atomic fission, the residue of which contains radioactive particles that are beta emitters. In these cases the successive emission of one beta particle places the resulting daughter element closer to the region of stability, and the residue or fallout from an atomic bomb produces large quantities of beta emitting radioactive dust. In addition to the beta particles that are emitted by such nuclei, many of the reactions likewise produce gamma rays.

All radioactive disintegrations result in the expulsion of a high velocity particle from the nucleus of the atom. According to Newton's third law, there is a reaction force to to every action force and this rule, when applied to the disintegration of a radioactive nuclide, would require that the daughter nuclide experience exactly the same reactive force as the emitted particle. More specifically, the momentum of the daughter product would be equal to the momentum acquired by the radioactive particle emitted in the opposite direction. Since momentum is defined as mass times velocity, a simple analysis shows that the recoil velocity of the particles is a function of the inverse of the masses of the disintegration fragments. Thus, in the case of the production of thorium of mass 234 by the emission of an alpha particle of mass 4 from the nucleus of the uranium atom of mass 238, the thorium atom will have a velocity of 4/234 of the velocity of the alpha particle.

In those instances where the atom is tightly bound, such as in a crystal structure, the daughter element may not actually leave the lattice structure of the crystal, and the energy will be dissipated in the form of heat. In the case of a liquid, the daughter product will initially acquire the velocity as given by the before-mentioned equation, and again the energy will be converted to heat. In the case of a gas, the daughter product will initially acquire the calculated velocity and the range of the particle will depend upon the density of the gases that the nuclides encounter. In a nearly perfect vacuum, such a particle could travel many hundreds of miles. At normal atmospheric pressure in air, however, the range of a recoil particle is less than one centimeter. Again the resulting energy is converted to heat.

Not all of the energy of a radioactive disintegration results in heat, but probably more than 99 percent of the energy ultimately results in heat in and near the location where the disintegration takes place. A little of the energy may be converted to infrared rays, light, ultra-violet rays, and gamma rays--rays that have a velocity of light and move in a straight line until they are absorbed.

Many induced radioactive disintegrations yield a smaller quantity of energy than is required to initiate the disintegration. In these cases, for instance, a 6 Mev alpha particle may produce disintegration with the emission of a proton having 4 Mev.

There are two general types of phenomena in which case the resulting energy is greater than the initial energy. The first type is the combining of light elements to form heavier elements among the lightest elements in the atomic table. This reaction is referred to as fusion. The nucleons in 4 hydrogen atoms exactly equal nucleons required to form one helium atom.

$$\begin{array}{lrl} & 4\ {}_1H^1 & = 4.0313 \\ & 1\ {}_2He^4 & = \underline{4.0026} \\ \text{Mass difference} & & = \ .0287 \end{array}$$

The annihilation energy of 1 atomic mass unit (amu) is 931 million electron volts (Mev). The energy resulting from this mass difference is expressed as follows:

$$\text{Energy} = (0.0287)\ (931) = 27\ \text{Mev}$$

The possibility that 4 hydrogen atoms will ever colide is rather remote. However, two atoms of deuterium likewise have the proper number of nuclides to form one atom of helium. Similarly calculated, this reaction gives a mass difference of 0.0256 amu and produces 24 Mev of energy. Similar reactions involving elements of hydrogen, helium, and lithium yield enough energy to make this a useable source of atomic energy. This is the principle of the operation of the hydrogen bomb.

Certain of the atoms among the heaviest atoms exhibit a different type of energy releasing reaction that is referred to as fission. Atoms such as uranium 235 easily absorb one additional neutron. The resulting atom ${}_{92}U^{236}$ is so unstable that it forms two groups of possible radioactive elements clustering around the middle of the atomic table. For instance, one possible reaction is the production of ${}_{55}Cs^{133} + {}_{44}Ru^{99} + 3{}_0n^1$.

$_{55}Cs^{133}$ = 132.9051 amu
$_{44}Ru^{99}$ = 98.9061 amu
3 neutrons = 3.0260 amu
TOTAL = 234.8372 amu

$_{92}U^{235}$ = 235.0439 amu
Total = 234.8372 amu
DIFFERENCE = 0.2067 amu

The difference between the mass of a single $_{92}U^{235}$ and the sum of the masses of the products of fission is of the order of 0.2067 amu or 192 Mev--about one tenth of 1 percent of the initial uranium 235 atom. Therefore, if all of the atoms in a kilogram of $_{92}U^{235}$ undergo fission, the mass annihilated is approximately one gram. By Einstein's equation Energy = Mc^2 one gram amounts to an energy of 9×10^{13} Joules and is approximately equal to the energy liberated by the explosion of 20,000 tons of TNT.

It is possible to control the liberation of energy by the atoms undergoing fission, and this source of atomic energy is used for the creation of unlimited energy in the atomic pile.

QUESTIONS

1. What is meant by a negatron emitter?
2. What is meant by a positron emitter?
3. How is the probability that a neutron will react with a particular nucleus expressed?
4. What is the approximate relation between the physical cross-sectional area of the atomic nucleus and the unit barns?
5. In order to remove neutrons from an atomic generating plant, cadmium rods are inserted. From this fact, what can you deduce about the neutron cross section of cadmium in barns?
6. Diagram a cyclotron and briefly describe its operation.
7. What is the advantage of the cyclotron over that of a high intensity polonium source?
8. Complete the following disintegration reactions:

$$_{2}He^{4} + {}_{11}Na^{23} \longrightarrow \ ? \ + {}_{1}H^{1}$$

$$_{2}He^{4} + {}_{10}Ne^{20} \longrightarrow \ ? \ + {}_{1}H^{1}$$

$$_{2}He^{4} + {}_{9}F^{19} \longrightarrow \ ? \ + {}_{1}H^{1}$$

$$_{2}He^{4} + {}_{14}Si^{28} \longrightarrow \ ? \ + {}_{1}H^{1}$$

$$_{2}He^{4} + {}_{13}Al^{27} \longrightarrow {}_{15}P^{30} + \ ?$$

9. When deuterons are allowed to bombard $_{7}N^{14}$, protons of considerable energy are observed being ejected. Write the disintegration equation.
10. When neutrons are allowed to pass through ordinary oxygen $_{8}O^{16}$, alpha particles are given off. Write the reaction.
11. Two atoms of deuterium $_{1}H^{2}$ with mass 2.01410 can combine to form one atom of helium. Calculate the energy released by this reaction.

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4 radioactivity safety and radiation doses

PLAN OF INSTRUCTION

OBJECTIVE

1. To familiarize the student with the hazards connected with radioactive elements.
2. To describe the units used to measure radioactivity.
3. To familiarize the student with the safe doses of radioactivity that the body can tolerate.
4. To study the types of rays and the hazards and limitations of each.
5. To study the instruments for measuring radioactive doses absorbed by the body.
6. To outline the special safety techniques for work with radioisotopes.

INTRODUCTION

1. Review the rays produced by natural and induced radioisotopes.
2. Review the absorption and penetration properties of alpha, beta, and gamma rays.
3. Review the half-life of radioactive substances and the relation between the half-life and the activity.

TEACHING PLAN

1. Introduce the unit of radioactivity (or the disintegration rate) the curie, and reduce this to number of radioactive disintegrations per second.
2. Introduce the unit roentgen and give the related value in terms of energy released and rise in temperature in human tissue.
3. Define the unit roentgen per hour, r/h, and the related milliroentgen per hour, mr/h.
4. Discuss the presently accepted maximum safe dosage as a function of physical health.
5. Discuss the normal radiation that the body is subjected to from cosmic rays, strontium-90, carbon 14, radon gas, etc.
6. Introduce the commonly used dosimeters.
    a. Quartz fiber electroscope dosimeter.
    b. Film badge monitoring dosimeter.
    c. Survey meters for measuring radioactive doses.
7. Discuss the extent of doses that an individual might normally receive in conducting experiments in this course. The amount of radioactivity used in performing the experiments in this course are at the microcurie level--comparable to the activity contained

in the human body. The exposure received in performing these experiments is completely negligible when compared with normal total exposure. Even so, radioactive material should not be eaten or inhaled unnecessarily, nor should it be left on the skin for any length of time. The simple safety precautions given in each experiment should be followed to avoid unnecessary exposure.

8. Safety precautions to be used with radioisotopes.

9. Washing highly radioactive glassware.

10. What to do if radioactive materials are spilled.

APPARATUS

None required.

RESOURCE MATERIAL

The measure of the quantity of x-radiation or gamma radiation is the unit roentgen, or r. This unit is defined in terms of the effect produced in air at a given point.

The roentgen is defined as the quantity of X-ray or gamma radiation that produces ions carrying one electrostatic coulomb of electric charge of each sign for each cubic centimeter of air at one atmosphere pressure and at 0^o centigrade. Another way to define the unit is to say that the radiation produces 2.083×10^9 pairs of charges in that volume. The radiation results in an energy loss in the beam and imparts an energy of 87.7 ergs/gram to the air. If the energy falls on human or animal tissue, the energy imparted to it is approximately 93 ergs/gram. Energy thus lost is converted directly into heat, and the increase in temperature produced in the tissue is approximately 22.4 millionth of a degree centigrade. The total energy of the beam is much greater than indicated by the above figure. The beam has a range of over 1,000 feet in air and decreases because of the inverse square law effect and because part of the energy of the beam is being absorbed along each centimeter of its path.

The number of r units that are absorbed by matter at a particular point will depend upon the intensity of the radiation and the length of the exposure. This is similar to saying that the temperature of water in a pot on a stove will depend upon the intensity of the heat source and the length of time that the heat is on. This unit is roentgen divided by time, or r/hr.

In practice, few laboratories have the facilities to measure either the electrical charge in statcoulombs or the increase in energy in ergs. Rather, the quantity of radiation is measured by an indirect method. Commercially manufactured dosimeters are available that will read the accumulated radiation directly by means of a fiber electroscope. This electroscope is first charged by a d.c. voltage and the ions produced by radiation discharge the electroscope. The electroscope is viewed by means of a small microscope arrangement and the fiber is seen against a calibrated scale. The scale can be made to read the quantity of radiation directly in r units.

An electrometer, an electronically amplified measurement of the ionic charge produced by the radiation, can be made to read in units of r/hr. Such a unit must be calibrated against a radiation field of known strength in order to read correctly. A standard field can be made by encapsulating a radium sample in a 0.5-mm-thick platinum capsule to absorb alpha and beta particles while permitting the gamma rays to pass through. The dose rate is then given by

$$r/hr = \frac{0.84m}{d^2}$$

where m = mass of radium in grams and d is the distance from the source in meters. Similar standards can be also made by encapsulating samples of other cheaper isotopes such as

$_{27}Co^{60}$, an isotope that can be purchased from several suppliers. For this isotope, the dose rate is given by

$$r/hr = \frac{1.35 \text{ activity in curies}}{d^2}$$

The unit curie gives the number of disintegrations per second. This unit is also founded on radium and specifically one curie is the radiation which is given off by one gram of radium. This turns out to be 3.7×10^{10} disintegrations per second. A microcurie is a quantity of radioactive material that disintegrates at the rate of 3.7×10^4 disintegrations per second.

The roentgen is defined only for X and gamma rays and is a measure of the strength of the radiation field or exposed dose. It is not a direct measure of the energy lost in various types of matter. The rad is defined for all kinds of ionizing radiation and is a measure of the absorbed dose, or energy absorbed per unit mass of material. The rad is defined as the absorbed dose of any nuclear radiation accompanied by the liberation of 100 ergs of energy per gram of absorbing material. In soft tissue an exposed dose of 1 r corresponds very roughly to an absorbed dose of 1 rad. The actual absorbed dose depends on the energy of the rays and the composition of the tissue, and may vary from 0.6 to 1.0 rad per roentgen.

The different kinds of radiation differ in their biological effect on tissue even when the absorbed doses in rads are equal. X or gamma radiation is the basis for comparison of the relative effect of other kinds of radiation. Both electrons or beta particles and positrons produce about the same biological effect as gamma rays. However, the relative biological effect, abbreviated RBE, of heavy ionizing particles such as alpha particles and fission fragments that may have a mass as great as 130 amu, produce a much greater biological effect for a given absorbed dose. RBE is the multiplier that must be used with the rad unit to yield the roentgen equivalent for man. This unit may vary from 0.6 to 20, depending on the type of rays and the energy of the radiating particle.

The roentgen equivalent for man, abbreviated rem, is the essential unit that describes the biological effect of radiation on man. Since the multiplier RBE is based on x and gamma radiation, and since the effect of beta and positron rays is about equal to that of gamma rays, the units of radiation in rem are almost equal to the original units in r. However, when the type of radiation involves heavier ionizing particles or when the radiation is due to a combination of types of radiation, the total rem exposure must be computed by calculating the several doses separately and adding the rem units.

Some special considerations must be made in the case of neutrons. Generally, a value from 5 to 10 for RBE has been recommended for neutrons and alpha particles. In view of recent developments in regard to the RBE of neutrons, it may be better to assume values of approximately 100 for these radiation, at least for biological effects on the eyes, where doses of neutrons are known to cause cataracts.

In the case of fast neutrons, a unit of dosage is used that is based on the pocket ionization chamber. This is done as a matter of convenience, since nearly every laboratory uses this particular type of instrument. The r unit for fast neutrons is defined as that amount of fast neutron radiation which will produce a 1-r reading in the Victoreen 100 mr bakelite-walled pocket chamber. This must be multiplied by RBE (as described above) to yield the rem unit for neutrons.

Standards have been set up by the U. S. Atomic Energy Commission for the case of gamma radiation in terms of roentgens. The same values are, however, also applicable for other types of radiation when reduced to rem units.

Zero to 25 roentgen in a period of 24 hours or less produces no radiation sickness or noticeable clinical effect. A person so exposed is not aware of any immediate biological damage and probably no serious biological damage has occurred.

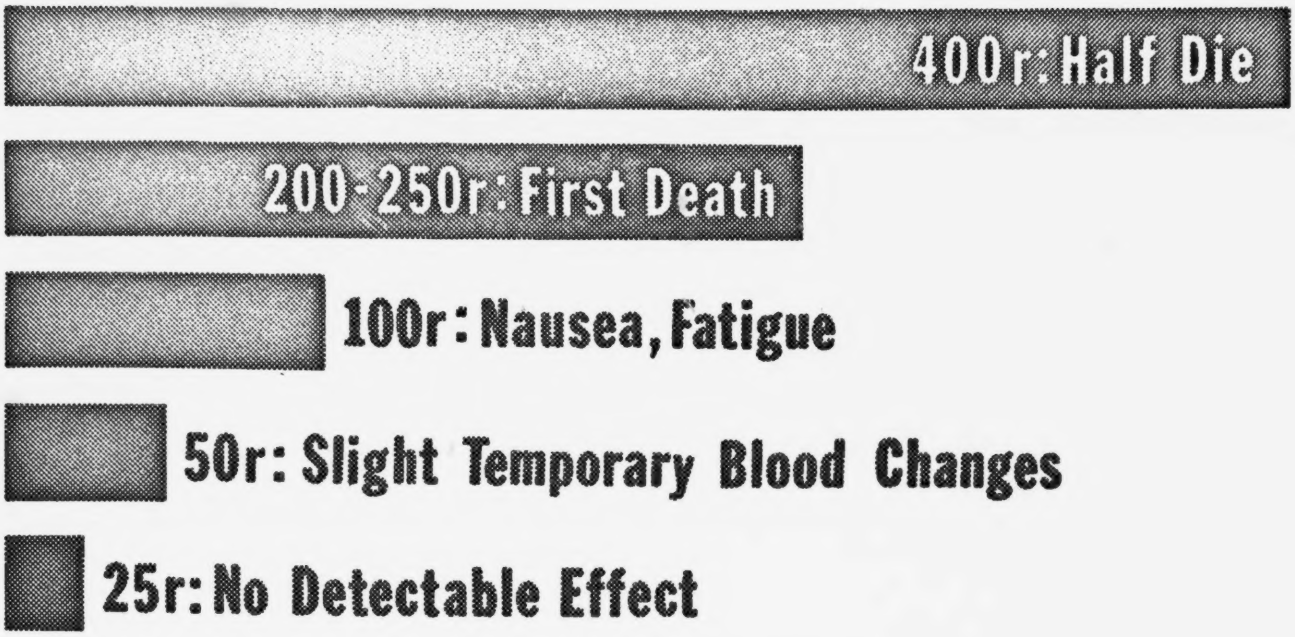

Fig. 4-1. Effects of external radiation

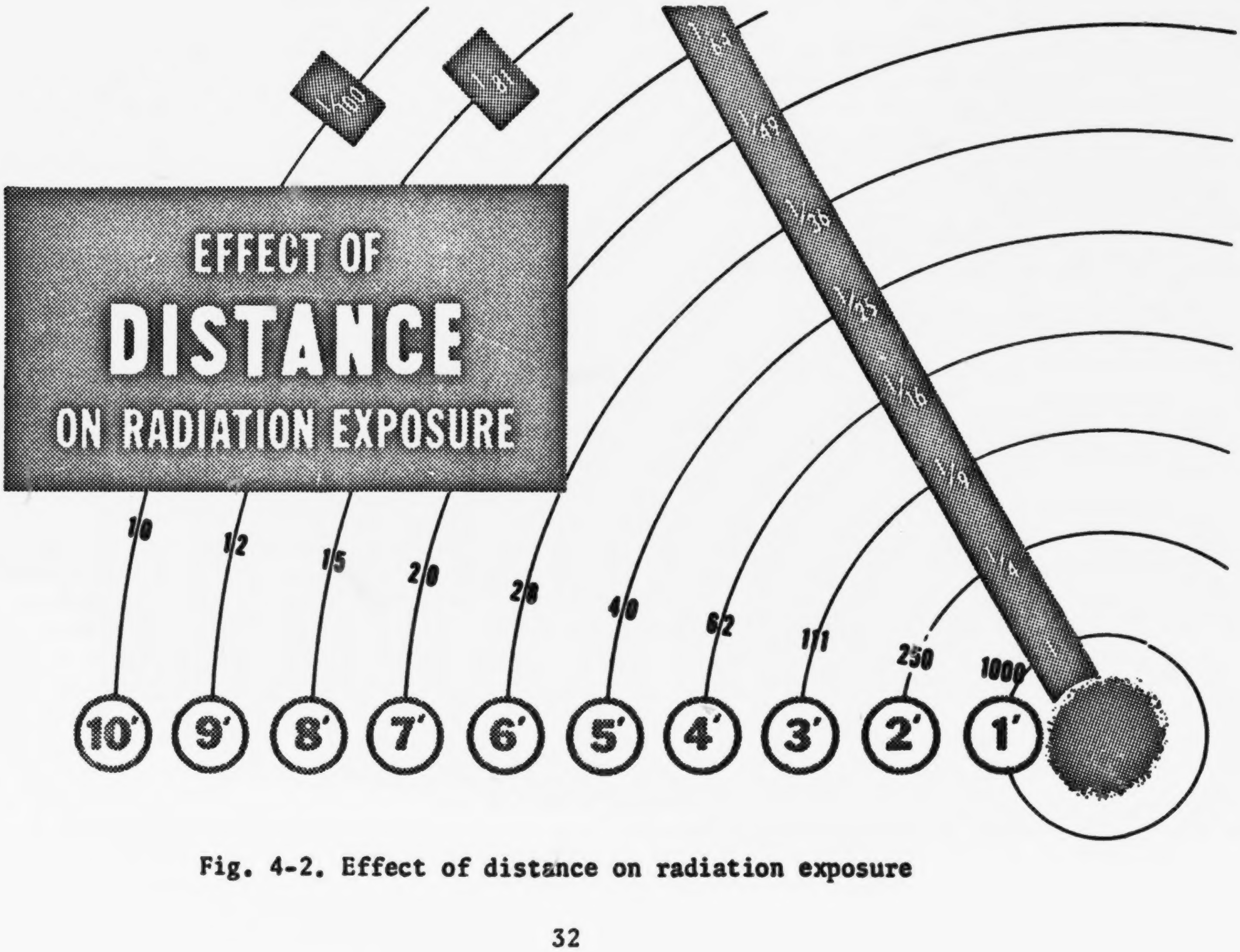
EFFECT OF
DISTANCE
ON RADIATION EXPOSURE
1/100
1/81
1/64
1/49
1/36
1/25
1/16
1/9
1/4
10
12
15
20
28
40
62
111
250
1000
10'
9'
8'
7'
6'
5'
4'
3'
2'
1'

Fig. 4-2. Effect of distance on radiation exposure

MAXIMUM PERMISSIBLE TISSUE DOSE
"REPS" PER WEEK

TYPE OF RADIATION	AT ANY POINT WITHIN BODY	RBE*	IN THE BASAL LAYER OF THE EPIDERMIS	
			EXPOSURE OF ENTIRE BODY	EXPOSURE OF HANDS ONLY
X-RAYS & GAMMA RAYS	0.3	1	0.5	1.5
BETA RAYS	0.3	1	0.5	1.5
PROTONS	0.03	10	0.05	0.15
ALPHA RAYS	0.015	20	0.025	0.075
FAST NEUTRONS	0.03	10	0.05	0.15
THERMAL NEUTRONS	0.06	5	0.1	0.3

*RBE - RELATIVE BIOLOGICAL EFFECTIVENESS

A radioactive dose of from 25 to 100 roentgen results in no radiation sickness but a slight temporary change in the blood. Individuals so exposed should be able to resume usual duties.

Table 4-1
MAXIMUM PERMISSIBLE TISSUE DOSE rem PER WEEK

Type of Radiation	At any point within body	RBE	Exposure of entire body	Exposure of hands only
X and gamma	0.3	1	0.5	1.5
Beta rays	0.3	1	0.5	1.5
Protons	0.03	10	0.05	0.15
Alpha rays	0.015	20	0.025	0.075
Fast neutrons	0.03	10	0.05	0.15
Slow neutrons	0.06	5	0.1	0.3

A person with from 100 to 200 roentgen suffers slight radiation sickness and a delayed recovery from changes in his blood. The delayed effects may shorten life expectancy by 10 percent.

A person exposed from 200 to 300 roentgens experiences a moderate radiation sickness but is likely to recover in three months unless complicated by poor previous health or infection.

Persons exposed from 300 to 600 roentgens can expect to suffer severe radiation sickness with up to 50 percent death for exposed individuals in from two to six weeks. An exposure of 450 roentgens results in possible eventual death to 50 percent of the exposed individuals.

A dose of more than 600 roentgens results in serious radiation sickness and up to 100 percent death for individuals during the first two weeks after exposure.

For workers employed in an installation where there is continual work in a radiation environment, the health tolerance level is set at 6.25 mr/hr for a 48-hour week. This means that a person could work in an environment where the radioactive level is 6.25 mr/hr and where a Geiger would record approximately 20,000 counts per minute for 48 hours a week without exceeding the national standard. In this time the worker would receive a total dose of 0.3 rem during the week. This dose is 0.1 of 1 percent of the dose that would produce sickness but not necessarily produce death. The body is continually being bombarded by rays similar to those from radioactive compounds, primarily from outer space. Each square inch of the body is bombarded by approximately one cosmic ray per second. Carbon-14, a radioactive substance found in all living matter, is continually emitting rays at the rate of 15 beta rays per minute per gram of living tissue, or for the body as a whole, 200,000 beta rays per minute. A like number of radiations are produced in the body from potassium-40, an integral part of the body. Additional rays come from radium in food and water, from radan in the atmosphere, from cesium-137, and strontium-90. A slight amount of uranium and other members of the radioactive series are found in the crust of the earth and these sources likewise produce a readable amount of radiation.

The total amount of radioactivity from these natural sources probably does not exceed 0.2 mr/hr, considerably below the health tolerance for man.

The problems involved in the safe handling of radioactive substances can be classified into three categories. These are: (1) protection of personnel, (2) control of contamination, and (3) disposal of radioactive waste. In the microcurie quantities available without a special license, the isotopes offer little hazard in any of these categories. However, the basic techniques involved in handling radioisotopes should be observed regardless of the quantities involved.

Hazards from radiation are classified as internal or external. Internal hazards have to do with radioactive materials entering the body. If the general rules for radiation laboratories are followed, there is no reason why any of the microcurie quantities available to schools should offer any hazard. It may be reassuring to know that therapeutic doses of phosphorus-32 up to 7 millicuries are given internally. For clinical treatment of hyperthyroidism, up to 10 millicuries of iodine-131 are given internally. These isotopes, ${}_{53}I^{131}$ and ${}_{15}P^{32}$, are available to the teacher only in 10-microcurie amounts, less than one-thousandth of the internal dose given.

External hazards from radiation include any exposure of the body to radiation from the radioisotopes. Alpha and beta particles are readily stopped by the usual glass laboratory containers or a thin sheet of aluminum. When the containers are kept closed, alpha and beta radiation is not considered to offer external hazards. Gamma radiation, which is very penetrating, is the major hazard.

The National Committee of Radiation Protection has recommended that the long-term exposure of the whole body shall not exceed 300 milliroentgens, or 0.3 rem, per week. For local exposure of the feet, ankles, hands, and forearms, the maximum permissible dose is 1,500 milliroentgens per week. The actual dose from the license-exempt quantities of gamma emitters can be calculated using the formula

$$R = 6CE$$

where R is expressed in milliroentgens per hour, C is the number of millicuries of activity, and E is the average quantum energy per disintegration in Mev. If the gammas are emitted in cascade with more than one per disintegration, the E factor is the sum of the energies of the gamma radiations. The following table indicates the dose rate and required time for some common gamma emitters in unlicensed quantities.

Table 4-2
ISOTOPE AND ENERGY OF GAMMA RADIATION

Isotope	Quantity, mc C	Gamma Energy (Mev) E	mr/hr at 1 ft. R	Hours for 1,500-mr dose
Iodine-131	0.010	0.367	0.022	68,000
Cobalt-60	0.001	1.3	0.014	107,000
Copper-64	0.050	1.2	0.036	40,600
Sodium-24	0.010	2.8	0.252	5,950

It is immediately obvious that none of these isotopes could be held long enough in the 168 hours per week to approach the maximum permissible dose of 1,500 milliroentgens per week.

The following set of simple rules is largely an adoption of the Oak Ridge Institute of Nuclear Studies safety regulations:

1. Whenever possible, work should be done with sealed samples of the radioisotope.
2. All work with unsealed radioisotopes should be carried out in trays. Any spills then be confined and can readily be decontaminated.

3. Rubber gloves should be worn when handling active solutions. The use of tongs and other devices to keep the activity from direct body contact is desirable.

4. Where vaporization may occur, the operation should be done under a fume hood.

5. Students with cuts should not work with radioactive materials unless approved rubber gloves are worn.

6. Eating, drinking, smoking, and use of cosmetics should not be allowed where radioactive materials are present.

7. Pipetting of radioactive solutions by mouth should not be done. Suction bulbs, spit traps, or other devices should be used.

8. All contaminated disposable materials should be placed in a labeled container for subsequent disposal.

9. Inhalation of radioactive materials should be avoided. Extremely small quantities of tritium, radon, etc., are highly toxic.

10. All glassware used for radioactive solutions should be kept separated from other non-contaminated glassware.

11. Hands should be washed after working with active solutions, and hands, clothing, and area should be monitored as a standard procedure.

12. Radioactive materials should be plainly labeled with the approved AEC labels and kept under lock when not in use.

13. A sign indicating what radioactive materials are being used should be displayed during any exposed experiment.

14. No protective clothing beyond the usual laboratory clothing is necessary in working with unlicensed quantities of radioisotopes.

15. An account of all radioactive materials received, used, disposed, or stored should be made.

With isotopes of short half-life in microcurie quantities, the liquid may be diluted and flushed down the drain with a large excess of water. Tissues, small animal carcasses, and other combustible materials may be incinerated without any hazard to personnel or community. Planchets and other non-combustibles can be placed in a covered, labeled container and disposed of in the regular trash collection.

Glassware should be well washed and rinsed, using any good laboratory detergent. See your supplier for detergents approved for radioactive matter.

In case of any spills, blot up the liquid with paper towels or cleansing tissue. Put the tissue in the can of radioactive waste. If a high level of radioactivity remains, wash the areas with a detergent and water. Soak up the liquid with paper.

QUESTIONS

1. Define the roentgen unit.
2. What is the effect on human tissue when a gamma ray is absorbed by the cell?
3. Describe a practical means of measuring the gamma radiation in the laboratory.
4. How would you calibrate an electrometer?
5. Distinguish between rem and RBE.

6. How are fast neutrons measured for radioactive safety purposes?
7. If a rate meter reading gamma rays indicates 15 mr/hr, how many hours per week may a person work in this environment?
8. In addition to lead, what absorbers are effective for alpha particles?
9. What is the range of alpha particles in a perfect vacuum?
10. What type of absorbers are effective for beta rays?
11. Why is it not possible to completely absorb the gamma rays from a source?
12. List all the types of radiation the body is exposed to due to natural effects.
13. Why is strontium considered more dangerous than phosporus as far as radiation is concerned?
14. Describe a correct method for pipetting radioactive solutions.
15. With samples of the magnitude used in this course, how could radioactive material be disposed at the completion of the experiment?

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5

geiger-mueller counters

PLAN OF INSTRUCTION

OBJECTIVE

1. To familiarize the student with the Geiger-Mueller counter.

2. To study the electrical circuit of the G-M tube.

3. To draw the counting-plateau curve for a typical G-M counter.

4. To study the resolution time of a G-M counter.

INTRODUCTION

1. Review the characteristics of the rays produced by radioactive elements.

2. Discuss absorption of radiation by elements and, in particular, the materials used in the construction of the G-M tube.

TEACHING PLAN

1. Diagram the function of the equipment with stress on the construction of the G-M tube, the purpose of the high voltage supply, the quenching gases, the discriminator, and the counting equipment.

2. Emphasize the precautions to be used in handling the fragile G-M tubes and the high voltages connected with this circuit.

3. Describe the formation of the ion pairs in the tube and the function of the gas, which permits the multiplication of ion pairs by collision.

4. Describe the action of the quenching gas and the ultimate destruction of the quenching gas as the result of the quenching in the tube.

5. Explain the rapid deterioration of the quenching gas when the voltages raise to a point where multiple pulses occur.

APPARATUS

G-M tube with rack to hold tube and sample

G-M scaler with variable voltage control

Timing system, such as a timer or clock

Sealed hard beta source, approximately 0.01 μc

Radium D + E (Atomic Accessories, Inc., Model SCB-84)

EXPERIMENTAL PROCEDURE

1. Attach the Geiger-Mueller tube to the high voltage circuit. Make certain that the high voltage control is rotated to zero voltage position.

2. Plug in the A-C cord, and switch the equipment to the "on" position.

3. Place a known radioactive sample, preferably an encapsulated sample, at a fixed distance from the G-M tube.

4. Slowly increase the voltage by rotating the voltage control knob until the counter begins to operate.

5. Make a set of five counting periods of one-minute duration each with the voltage control at a point where the counter just begins to operate.

6. Make a series of determinations in steps of twenty volts and record the average number of counts in a one-minute period.

7. As the voltage on the G-M tube is raised beyond the plateau region, the rate of counts will be seen to increase very markedly. If the voltage is raised too high, the tube will produce multiple counts. This will result in counts with or without the radioactive sample. Caution: Do not leave the voltage in this region because it will seriously affect the life of the tube.

8. Plot the data obtained in this experiment on a chart with the number of counts per minute as the ordinate and the voltage as the abscissa.

9. Identify the horizontal or plateau portion of the counting rate versus the voltage curve. The proper operating voltage of the G-M tube is on the plateau but with the lowest voltage that gives consistent counts.

10. Calculate the percentage increase in the observed count per 100-volt increase. To do this, divide the increase in counts by the number of counts and divide this by 100. A value of 0.03/100 to 0.1/100 is considered satisfactory.

11. Repeat the series without the radioactive sample. This will give the average background count for each voltage setting.

12. Subtract the average background reading for each voltage setting to arrive at the average.

13. Plot the counts due to the sample and compare with the chart plotted in No. 8 above. Will the plateau determined in No. 8 remain constant during the life of the G-M tube?

RESOURCE MATERIAL

A great variety of counters can be constructed to measure the ionization produced by radioactive rays. The Geiger-Mueller counter is an outgrowth of a series of much simpler counters designed to measure ionization.

If two metallic surfaces are charged with a d-c voltage and if ionization takes place between the surfaces, the negative charges will drift toward the positively charged surface and the positive charges will drift toward the negatively charged surface. The type of gases between the surfaces and the shape of both the surfaces and the enclosing container have an effect on the results. Another important consideration is the voltage applied to the conducting surfaces.

From a practical standpoint, a limited number of gases are suitable for use in a counter. Gases such as carbon dioxide, water vapor, oxygen, and nitrogen have a high affinity for free electrons and are unsuitable. Helium and argon, on the other hand, exhibit characteristics that are ideal.

While it is possible to build counters with parallel surfaces, a counter consisting of a cylindrical conductor and a center wire of small radius is more desirable because the cylindrical unit will operate at a lower d-c potential.

Counters can be made to operate at atmospheric pressures, but the efficiency is increased if the counter is filled with a gas at reduced pressure. A pressure of 10 cm of mercury is frequently employed. If a counter operating at reduced pressure is used, the conducting surfaces must be enclosed in a container of some sort. Since a ray passing through matter of any type loses some energy due to absorption of part of the energy, the selection of the material in which the conductor is housed is of utmost importance. In those cases where the radiation is extremely weak, it may be desirable to have no absorption. In such cases, the radioactive material in the form of a gas is pumped through the counter at reduced pressure. This technique is referred to as gas counting and is especially useful to detect weak alpha and beta particles.

Cylindrical counters with very thin mica windows are useful for detecting alpha particles and low-energy beta particles, such as those from carbon-14. Window thicknesses are measured in milligrams per square centimeter (mg/cm^2). To count alpha particles, the window thickness should be under 2 mg/cm^2. Windows with a thickness of 3 to 4 mg/cm^2 are useful for measuring high-energy beta particles, such as those from phosphorus-32.

Thin-wall glass tubes with the inside cylindrical conductor made of a metal coating on the inside of the glass tube are used to detect high-energy beta rays and gamma rays. This type tube has a wall thickness approximately 30 mg/cm^2 and will not detect alpha rays and weak beta rays. This type tube is used in many beta-gamma survey meters.

The G-M tube is developed from the two electrode ionization chamber and in its simplest form consists of a hollow metallic cylinder, charged with a negative voltage, and an anode wire, which is charged positively. Any ions produced by radiation in the area between the two conductors is attracted to either the anode or the cathode cylinder. With the use of helium or argon gas in the tube, the free electrons produced by the ionization are not captured by the gas and, consequently, drift toward the anode wire. The positive ions, being heavier, drift slowly toward the negatively charged cylinder.

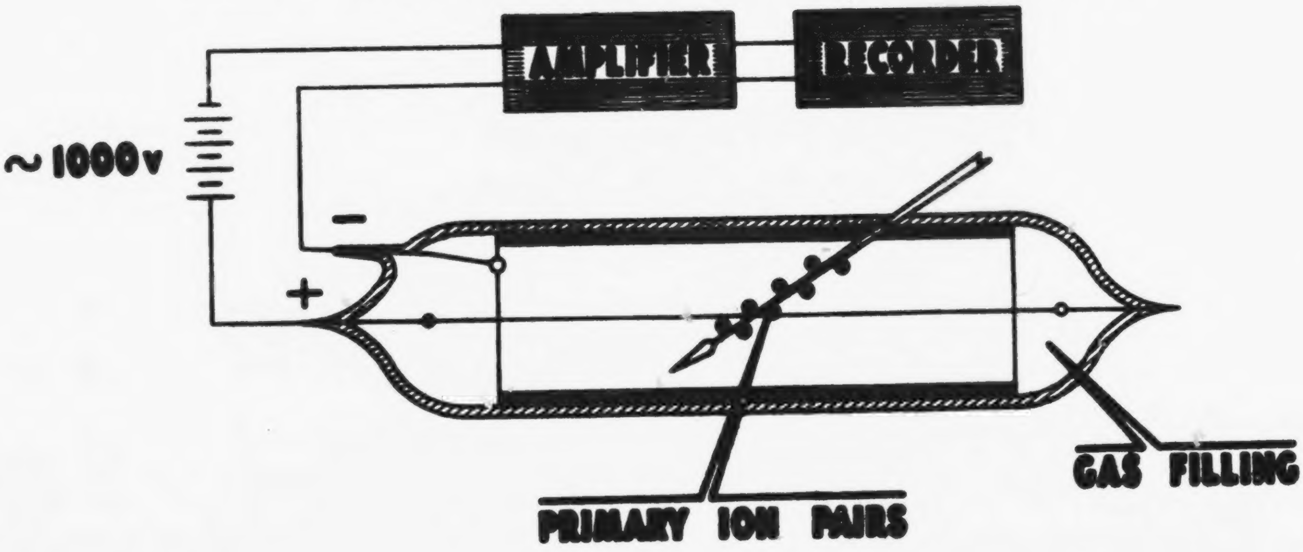
There are several conditions of operation that are controlled almost entirely by the voltage applied to the conductors:

1. When the voltage is very low, the charge that reaches the conductor depends upon the field due to losses as a result of recombination, i.e., electrons recombining with the positive charges produced by ionization.

2. If the voltage is increased, a plateau is reached where the loss due to recombination is negligible, and the pulse size is independent of the voltage but is dependent upon the amount of ionization produced in the tube. Under these conditions, the quantity of charge collected on the center wire may vary by a factor of 1,000 and will depend upon the type of radiation and the energy of the radiated particle (alpha particles produce the greatest amount of ionization).

3. If the voltage is increased beyond the plateau region, the velocity of the electron (as it is moving toward the cathode in the center) reaches a point where the electron is able to create new electrons by collision with the gas particles in the tube. This condition is referred to as an avalanche and is the result of the electron amplification due to the gas in the tube. The ratio of the total current to primary ionization in the region is called the gas amplification factor. Amplification factors of 10,000 or more can readily be achieved in such tubes. In this region the total current produced by the primary ionizing particle is still

THE GEIGER-MÜLLER COUNTER

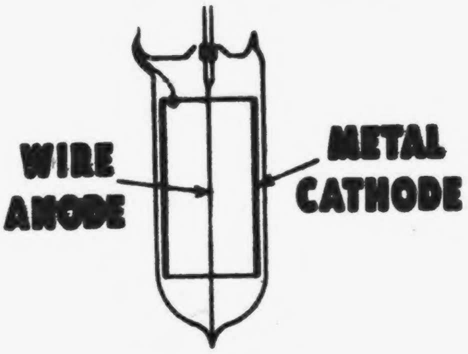

AMPLIFIER
RECORDER
~1000v
−
+
GAS FILLING
PRIMARY ION PAIRS

MATERIALS AND FILLING SUITABLE FOR α, β, γ, OR NEUTRONS

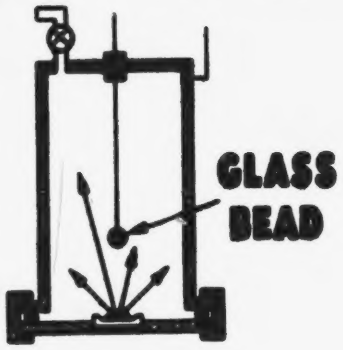
THIN CENTRAL WIRE GIVES HIGH FIELD FOR AVALANCHES

1 OR 1,000,000 PRIMARIES GIVE SINGLE PULSE

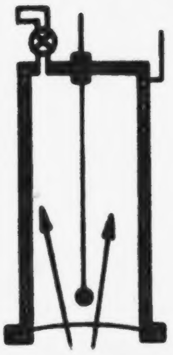
TYPES OF GEIGER-MÜLLER COUNTERS


WIRE ANODE
METAL CATHODE

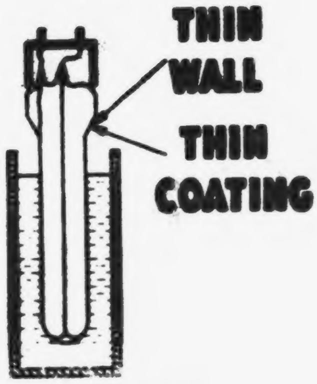
COMMON TYPE



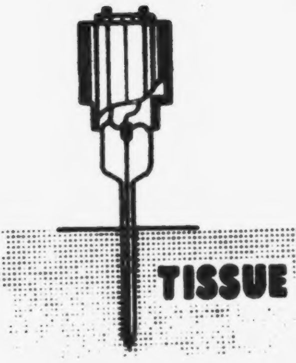
INTERNAL COUNTER



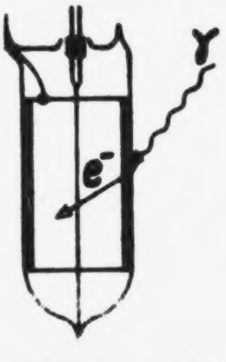
THIN WINDOW β COUNTER


THIN WALL
THIN COATING

IMMERSION β COUNTER

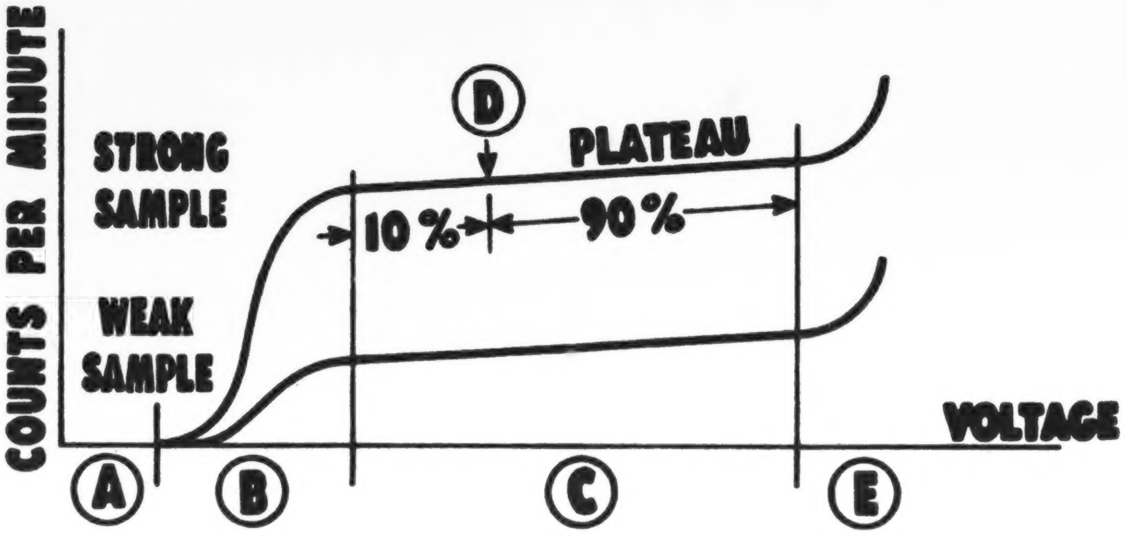


TISSUE PROBE



BISMUTH WALL COUNTER

THE GEIGER—MÜLLER PLATEAU



Ⓐ NO PULSES LARGE ENOUGH FOR RECORDER

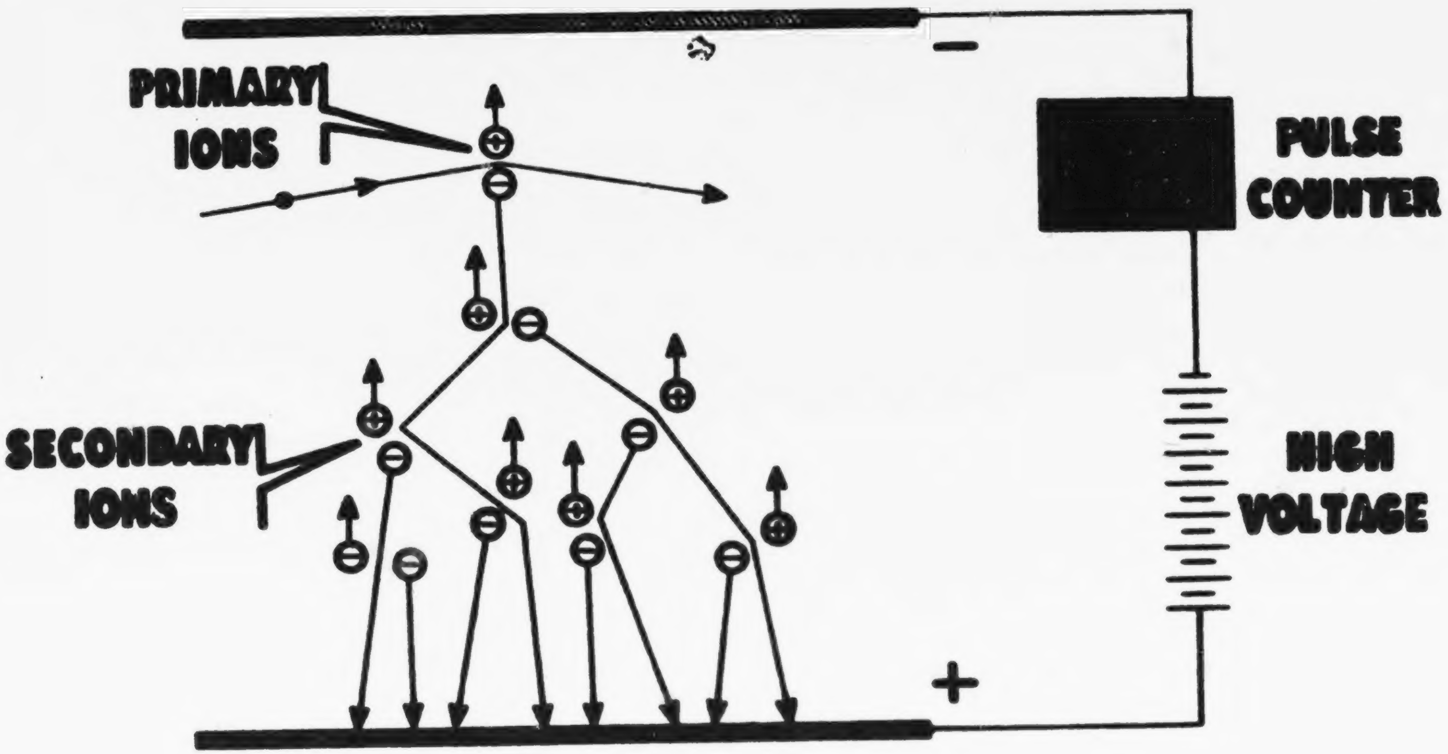
Ⓑ AVALANCHES GROW LARGER WITH VOLTAGE
NUMBER OF RECORDER PULSES INCREASES

Ⓒ ALL PARTICLES TRIGGER MAXIMUM AVALANCHE
ALL PULSES RECORDED

Ⓓ OPTIMUM SETTING FOR OPERATING VOLTAGE
HIGHER VOLTAGE GIVES SHORTER TUBE LIFE

Ⓔ SPURIOUS DISCHARGES LEAD TO BREAKDOWN

GAS AMPLIFICATION


–
PRIMARY IONS
PULSE COUNTER
SECONDARY IONS
HIGH VOLTAGE
+

- ELECTRONS RECEIVE ENOUGH ENERGY TO IONIZE
- AVALANCHE OF SECONDARIES
- CURRENT MULTIPLIED BY 1.000 TO 1.000.000

proportional to the original ionization. This region, like the previous region, is also a proportional region. The amplitude of the signals are larger, however, so that it is easier to measure the effect.

4. If the voltage is further increased, the total current produced by the avalanche is no longer strictly proportional to the initial ionization. This region is called the region of limited proportionality. Counting tubes are rarely adjusted to operate in this region.

5. If the voltage is increased beyond the proportional range, a region is approached where the amplitude of all pulses is the same, whether they are caused by massive ionization from alpha particles or produced by a single electron initiated by a gamma ray. This is called the Geiger threshold. If the voltage is increased beyond this point, a continuous arc will form in the counter and the current through the counter will be limited solely by the external circuit. A tube operating at a voltage beyond the Geiger threshold must incorporate some method to quench the discharge produced by each radioactive ray.

   With a quenching feature incorporated in the tube, the pulse height produced by the counter will be independent of the amount of initial ionization, and the number of counts per minute will be independent of the voltage applied to the counter. This region is referred to as the Geiger plateau.

6. If the voltage is increased beyond the Geiger plateau, multiple pulses are produced by each ionization, and the tube produces an uncontrolled series of pulses.

The voltages at which the various phenomena take place differ from tube to tube but are generally proportional to the diameter of the outside cylinder and inversely proportional to the diameter of the wire anode. Typical regions are as follows: below 600 volts, proportional counting; 620 to 800 volts, Geiger plateau region; above 850 volts, multiple pulsing. Operating voltages to place commercially available tubes on the plateau vary from 700 to 1300 volts.

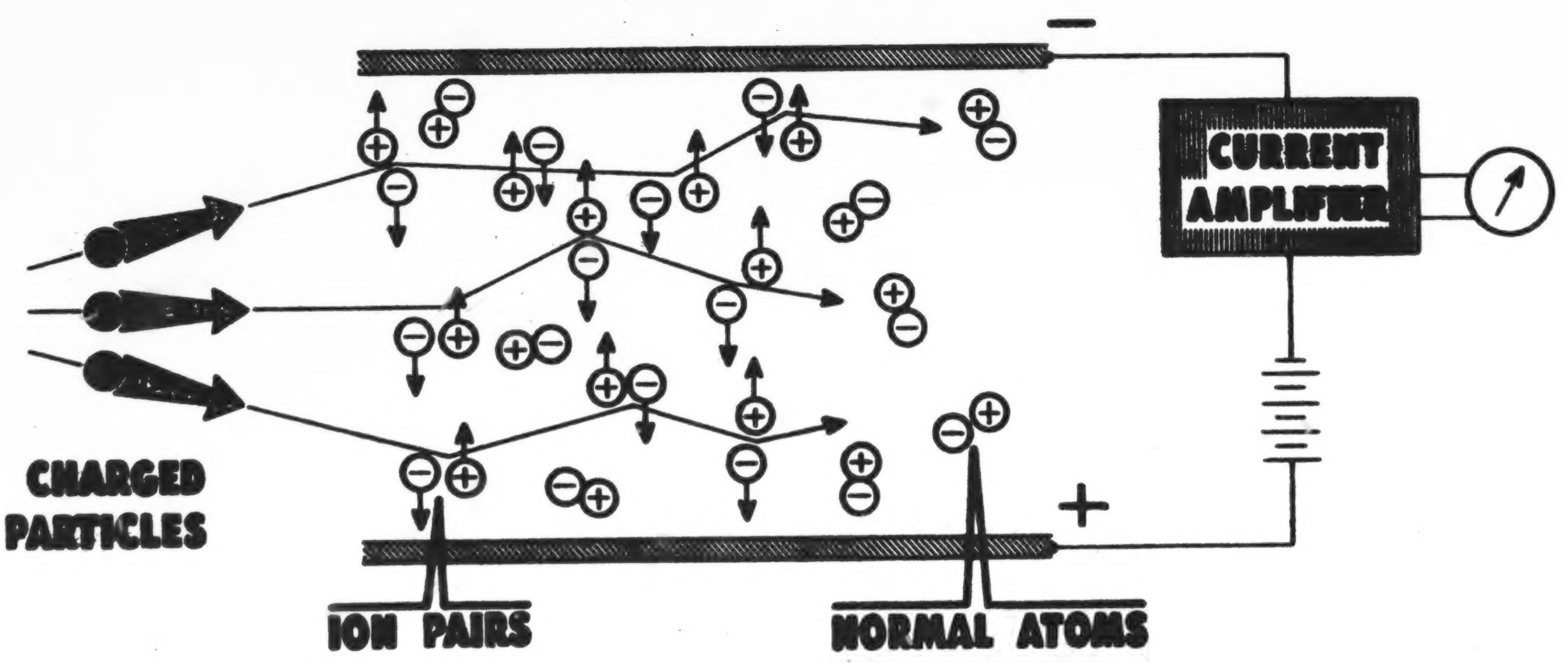
The arc in a counter tube can be extinguished electronically by applying a voltage in such a manner that the voltage across the tube drops below the Geiger plateau immediately after the pulse has been registered. This method is not normally used in commercially available equipment.

Most G-M tubes employ a second gas in the tube to perform the quenching function, and tubes of this type are referred to as self-quenching tubes. One of a series of organic gases may be mixed with the helium or argon in the G-M tube. Satisfactory gases for this purpose are alcohol, amyl acetate, xylene, butane, and others.

The function of the second gas is to quench. The original ionization particle produces one or more electrons in the counter. Since the center wire is positively charged, the electrons drift toward the wire going faster and faster and reaching tremendous speed as they approach the intense field near the wire. When they reach a critical speed, they may dislodge more electrons from the gas atoms. Each ionization thus produced produces a pulse of ultraviolet light that may dislodge an electron from a nearby gas molecule. This phenomenon spreads the avalanche up and down the G-M tube so that a sheath of ions is formed around the center wire. It is this sheath of ions consisting of a billion or more electrons striking the wire along its length, producing sharp pulses.

During this time, the positively charged helium and organic gas ions are moving more slowly toward the outer cylinder, attracted by the negative charge. As the helium ions move, they collide with the organic ions, extracting electrons from them and forming neutral helium atoms. By the time the positive ions reach the wall, they consist primarily of organic ions. Electrons from the wall neutralize the organic ions, and the energy released in the neutralization is absorbed by the dissociation of the organic molecules. Some of the

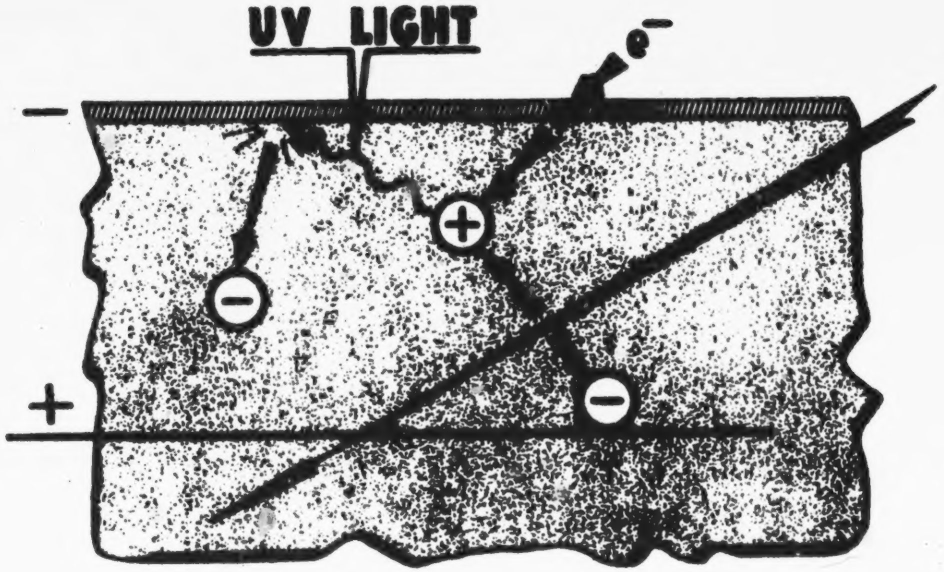
IONIZATION CURRENT


CURRENT AMPLIFIER
−
+
CHARGED PARTICLES
ION PAIRS
NORMAL ATOMS

. INCOMING PARTICLES IONIZE ATOMS
. ELECTRODES ATTRACT IONS
. ARRIVAL OF IONS CONSTITUTES CURRENT
. CURRENT IS MEASURE OF PARTICLES

NEED FOR QUENCHING

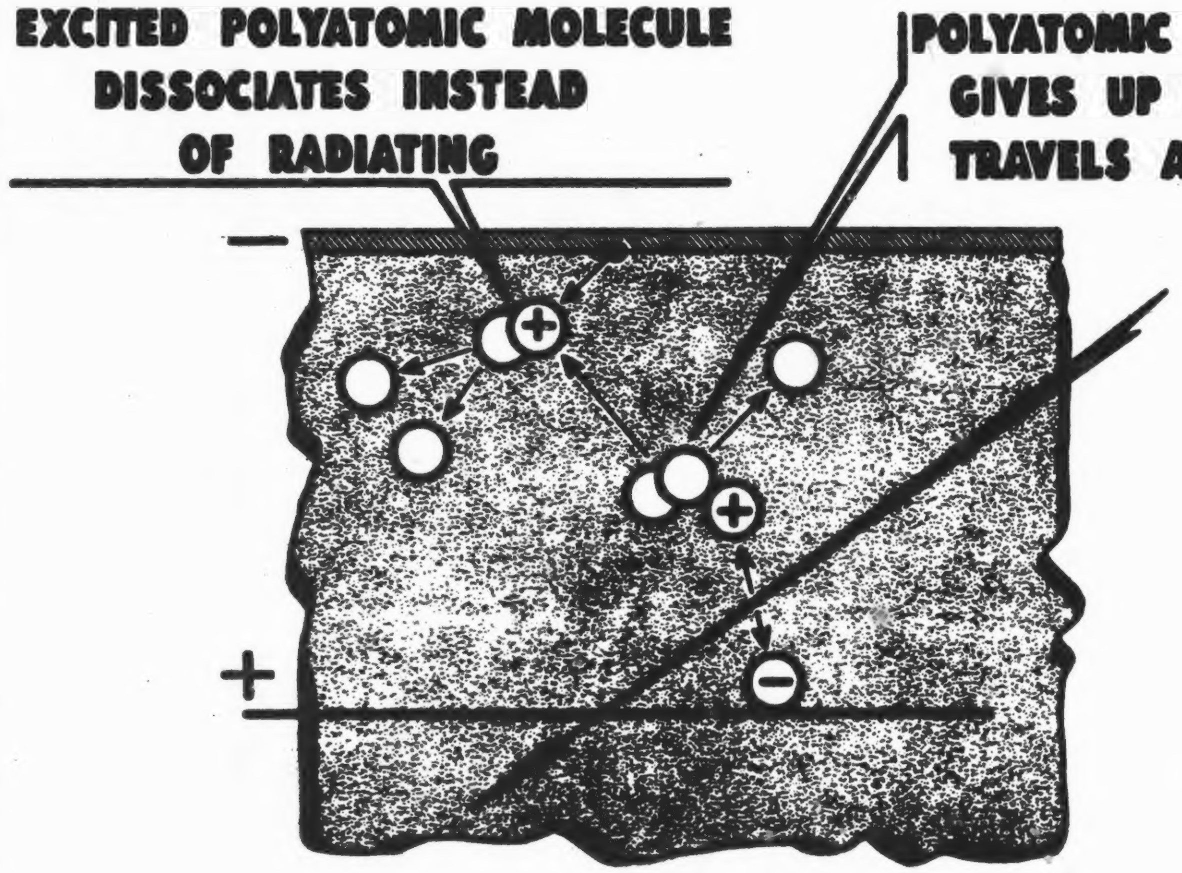
IN G-M TUBE



- POSITIVE ION DRAWS ELECTRON FROM CATHODE
- ION BECOMES EXCITED ATOM
- ATOM RADIATES IN ULTRAVIOLET
- LIGHT EJECTS PHOTOELECTRON FROM CATHODE
- ELECTRON INITIATES FURTHER CASCADES

ACTION OF QUENCHING GAS

IN G-M TUBES



EXCITED POLYATOMIC MOLECULE
DISSOCIATES INSTEAD
OF RADIATING

POLYATOMIC MOLECULE
GIVES UP ELECTRON.
TRAVELS AS + ION

TYPICAL GAS

.90% ARGON

.10% ETHYL ALCOHOL OR
AMYL ACETATE, ETC.

NEARLY COMPLETE SUPPRESSION OF SPURIOUS COUNTS

BUT...

DISSOCIATION OF GAS LIMITS USEFUL LIFE

organic gas in the counter is removed by dissociation each time an avalanche is quenched in the tube. Tubes filled with such gases have an expected life of from 10^9 to 10^{10} counts.

G-M tubes may also be filled with halogen gas (one of the chlorine-type gases), such as a tube filled with a neon-halogen mixture. Such tubes are extremely stable with practically infinite life but are not as sensitive as organic gas quenched tubes. They are neither damaged by over voltage nor affected by temperature change and are not photo sensitive.

A typical G-M tube is constructed by evacuating the tube and admitting alcohol vapor until the pressure has risen to 1-cm reading on a mercury manometer. The argon is then admitted until the pressure rises to 10 cm.

One of the important characteristics of the tube is the slope of the counting plateau. The slope is measured in percentage increase per 100 volts. A slope of 0.03/100 v is considered excellent, and a slope of 0.1/100 v is considered satisfactory.

One of the major defects of a G-M tube is the time lag from the beginning of the avalanche of electrons in the tube until the tube is restored to normal by the action of the quenching gases. A time delay of the order of 100 to 500 micro-seconds is involved in the quenching process and, therefore, the maximum pulse rate that can be accurately measured is only a few hundred per second. Corrections must be made for the error in the counting rate because of the insensitivity of the tube during the recovery time.

Since the disintegration of the radioactive nuclides is based on probability, the pulses produced are random and not equally distributed in time. This further reduces the maximum counting rate capability of the G-M counter. When the counting rate is of the order of 1,000 counts per minute, it is necessary to add a correction, referred to as the coincident correction, to account for the rays that pass through the tube during the insensitive period.

An entirely different correction must be made when the counting rate is very low. The G-M tube is sensitive to not only alpha, beta, and gamma rays but also to cosmic rays and to the photo-electrons produced by high-energy photons. Tubes are often shielded from photons by painting the glass cylinder with an opaque black paint, but this has no effect on cosmic rays. Shields with thicknesses from two to three inches made of lead or iron are typically used to reduce the background count due to cosmic rays, and it is possible to reduce the background count to approximately 25 percent of the initial background count. The background count, or the count with no radioactive sample, must be made before and after each reading and must be subtracted from the total counts recorded by the G-M counter. Inasmuch as the background count is also based on probability, the count will vary considerably in successive equally spaced counting periods. The same care and series of counts must be made to determine the background count as are made to determine the counting rate of the sample.

QUESTIONS

1. Diagram a simple G-M counter system.
2. Why is it more desirable to apply a positive voltage to the central element than a positive voltage to the outer cylinder?
3. What part do photo-electrons play in the G-M tube?
4. How is the G-M tube operated to produce an output proportional to the intensity of radiation?
5. Alpha particles may be distinguished from beta particles by using the G-M tube in the proportional counting region. Explain how this is done.
6. What is the effect on alpha particles of a thick window on the G-M counter tube?
7. Describe in your own words the avalanche of electrons produced by an ionizing ray.
8. What is the function of the helium gas in the G-M tube?
9. What is the function of the gases such as alcohol, butane, etc., in the G-M tube?

10. A neon-halogen mixture is commonly used in G-M tubes. What advantage does the halogen-type tube have over the alcohol-type tube?
11. Define the slope of the counting plateau.
12. What is the approximate dead-time of a G-M tube due to the action of the quenching gas?

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6

determination of half-life

PLAN OF INSTRUCTION

OBJECTIVE

1. To study the behavior of radioactive isotopes.
2. To formulate the rules governing the decay of radioactive substances.
3. To determine the half-life of a radioactive isotope.
4. To become cognizant of the possibility of a radioactive daughter product and its effect on measurements.

INTRODUCTION

1. Review the three types of radioactive rays generally produced by radioactive substances--alpha, beta, and gamma rays.
2. Review the radioactive series in general for the heavy elements, i.e., above lead in the atomic table.
3. Review the units of radioactivity (curies and microcuries) and indicate how this affects the counting rate of the G-M counter.
4. Review the source of energy with which the radioactive ray is emitted from the nucleus of the atom. The mass loss is converted into energy according to Einstein's energy equation, $E = mc^2$. Most of this energy appears in the motion of the particle and is dissipated in the form of heat.

TEACHING PLAN

1. Discuss the reason for using a radioactive isotope similar to I^{131} rather than one of the uranium or thorium series radioactive isotopes. (Available from Nuclear-Chicago, Inc., as RCB-1, Iodine-131.)
2. Note that a careful selection of the radioisotope with a stable daughter product makes it possible to isolate the activity of a radioisotope from the activity produced by the radioactive daughter.
3. Introduce the concept of half-life, wherein the activity of the sample decreases to one-half the initial activity in a period of time that is characteristic of the radioisotope.
4. Develop the power series that will show student the following concerning half lives: Activity after intervals of 1, 2, 3, or 4 will fall off as the power series, 1/2, 1/4, 1/8, or 1/16 of its initial value.
5. Show that this series can be written as $A_n = A_o \times 2^{-n}$.

6. Introduce the concept that radioactive decay is a random process. It can be described in terms of probability, and the average number decayed in the time interval dt can be given as $dN = \lambda N dt$, where λ is the disintegration constant.

7. Point out that it is not easy to determine the average number that decay (-dN) in a time interval. A counting device such as a Geiger-Mueller tube does not record all of the decay particles because of the following factors:

   a. The geometry of the radioactive sample and the size of the tube
   b. The absorption of some of the rays by air or other absorption materials
   c. The scattering resulting from the collision of a ray with a heavy nuclei

8. Introduce the concept of plotting the radioactive decay on semi-log paper, where the activity is plotted as the ordinate on a logarithm scale and the time is plotted as the abscissa as a linear function.

9. Diagram on the blackboard a curve similar to that shown on p. 19 of Laboratory Experiments with Radioisotopes, USAEC, and draw a straight line through the points on the chart.

10. Discuss briefly the theory of least squares in connection with observed points in probable occurrences and the most probable curve that represents the information.

11. Determine from the above straight line the half-life of a radioactive sample.

APPARATUS

G-M tube with rack to hold tube and vial

G-M scaler with variable voltage control

Timing system, such as a timer or clock

5 ml, 10 uc vial of sodium iodide

Note: Because of its short half-life, sodium iodide is available only at stated times each year. The instructor should contact the supplier of this isotope and perform the experiment when the supply of ${}_{53}I^{131}$ is available.

EXPERIMENTAL PROCEDURE

1. Obtain a vial of about ten microcuries of I^{131} (as sodium iodide) solution and arrange this in the counting stand so that it is possible to replace the vial for repeated tests. Leave the relative geometry between the G-M tube and the vial as constant as possible. It is not necessary to open the vial.

2. Switch on the G-M counter and allow it to warm up. Adjust the voltage to the lower portion of the plateau.

3. ${}_{53}I^{131}$ emits both gamma and beta rays. In order to limit the observed rays to gamma rays, a beta metallic shield should shield the G-M tube.

4. Observe and record the counts for one minute.

5. Take five one-minute readings, and average the counts obtained in the five intervals.

6. Take a similar number of readings on the background count.

7. Record the day and time of observation.

8. Make observations over a period of two weeks at suitable intervals and record the number of days elapsed since the first record and the number of observed counts per minute.

9. List the net count per minute that is obtained by subtracting the background count from the observed counts per minute.

10. Take the initial observed counts per minute as unity activity.

11. For the subsequent counts, divide the net counts per minute by the initial count to arrive at the activity expressed as a decimal and less than one.

12. Plot the activity as the ordinate on the log scale against time in days as the abscissa on the linear scale. This graph is referred to as a semi-log graph.

13. Draw the most reasonable straight line through the plotted points and determine the half-life directly from the graph.

14. Compare this with the published half-life for I^{131} of 8.08 days.

15. Calculate the disintegration constant, λ, from the half-life obtained in 14.

16. Assuming that all of the material in the vial was ${}_{53}I^{131}$, calculate the number of disintegrations per second for the radioisotope.

RESOURCE MATERIAL

The phenomena of radioactivity is one of probability. One of the characteristics of events that are governed by probability is that the rate at which the event takes place is proportional to the number of interacting factors. While it is impossible to predict when a particular nucleus will undergo a disintegration, the rate at which disintegrations occur is a constant.

One of the simple ways of defining this constant is to define the half-life of the radioactive nuclide. The half-life is the length of time that is required for one-half of the radioactive material to undergo disintegration. Figure 6-1 shows the curve illustrating the decay of a radioactive nuclide having a half-life of three hours. Starting with an initial radioactivity of 100, or unity, the activity is reduced to one-half the activity in a period of three hours. In a second three-hour period the activity is reduced from the activity at the end of the first three-hour period to one-half of that value, or to 25 percent of the original activity. At intervals of continuing half-lives, the activity is reduced by one-half for each half-life period.

There is no way by which the nuclear disintegration can either be speeded up or slowed down; it is one of the characteristics of the half-life. The half-life period of a nuclide is often used to positively identify the nuclide.

The experiments performed in this session are limited to a simple radioactive decay. One of the isotopes of iodine ${}_{53}I^{131}$ has a conveniently short half-life of 8.05 days. Both beta and gamma rays are emitted by the nuclide, which then forms ${}_{54}Xe^{131}$, one of the stable isotopes of the inert gas xenon. This particular isotope is ideal for an elementary experiment in nucleonics. The activity of the radiation may be seen by observing the gamma rays that pass through the glass enevelope of a vial containing iodine in the form of sodium iodide. The vial need not be opened. Therefore, no contamination can result from the radioisotope. Furthermore, the daughter nuclide is stable and will not produce additional activity. If the daughter product is radioactive, the measurements will include both the activity due to the parent and the activity due to the daughter nuclide. Such an experiment will be performed during a later session using lead-210. Furthermore, this nuclide is readily available and disintegrates through several half-lives in a relatively short period.

2

The activity of a radioactive sample decreases as a simple power series, 1, 1/2, 1/4, 1/8, 1/16 . . . . $1/n^2$ where n is the number of half-lives that have passed since the initial reading was made.

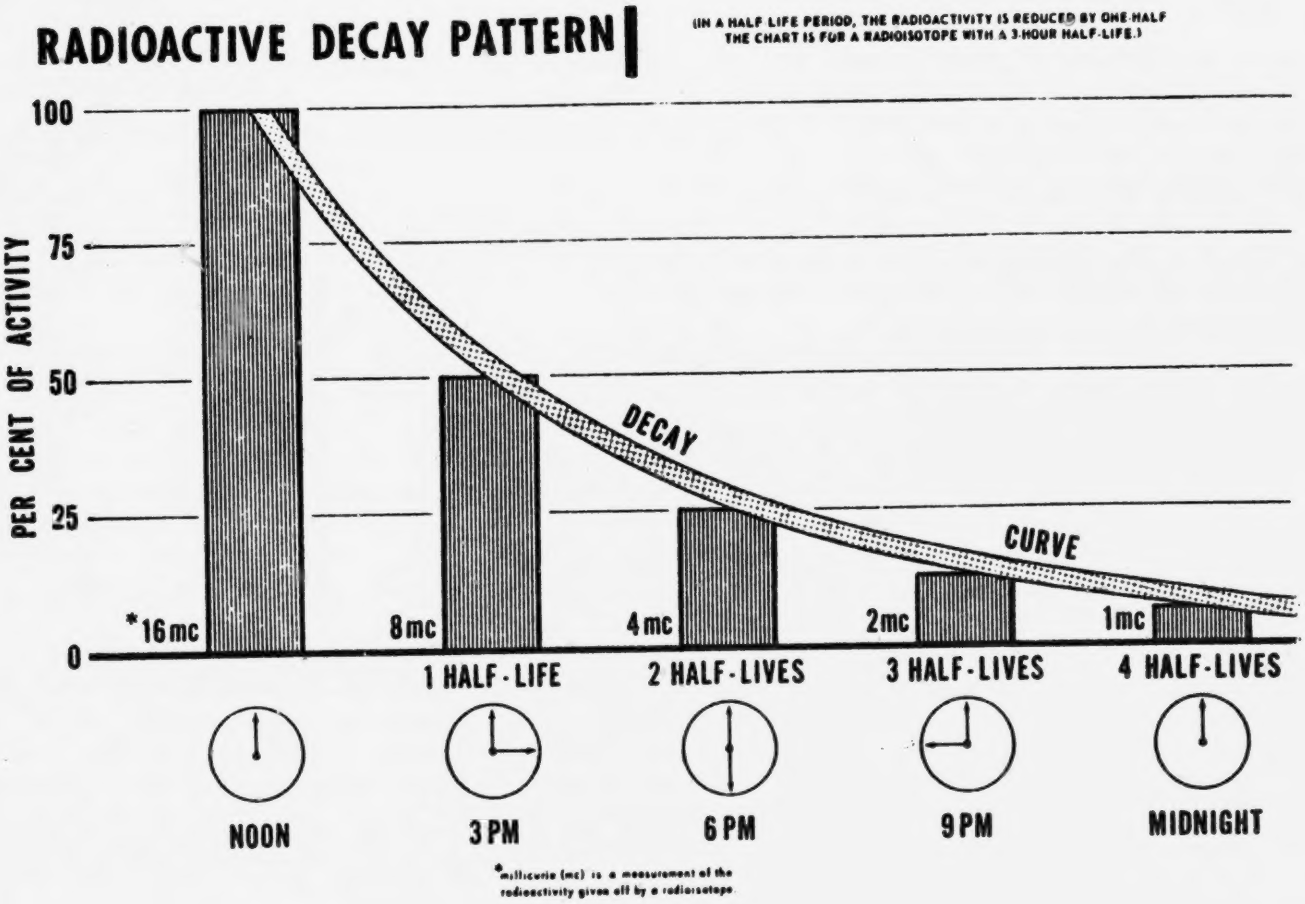

Fig. 6-1. The decay of a radioactive nuclide with a half-life of three hours

This equation can also be written as

$$A_n = \frac{A_o}{2^n}$$

where A_n is the activity at the end of n half-lives, A_o is the initial activity, and n is the number of half-lives.

The number of disintegrations per second produced by a sample can be obtained from the general differential equation

$$-dN = \lambda N dt$$

This equation can be simplified to give the number of disintegrations per second by

$$\text{disintegrations per second} = \lambda N$$

where N is the total number of radioactive nuclides and λ is the disintegration constant. The disintegration constant is related to the half-life of the element and is

$$\lambda = 0.693/T$$

where T is the half-life in seconds.

N can be calculated by dividing the weight of the sample in grams by the molecular weight of the sample and multiplying this by 6.0427×10^{23}. The disintegration constants are known for many substances and may be found in tables describing the characteristics of radioactive nuclides.

The reverse process is used to determine the half-life of radioactive elements that have half-lives of several thousand to a billion years. Obviously, no one has observed such elements long enough to see the activity decrease materially, much less decrease to one-half the original activity. It is only necessary to measure the activity of a known mass of material in disintegrations per second. Special precautions must be taken in order that the counting system actually is reading the total number of disintegrations per second. With the number of disintegrations per second and the total number of nuclides that can be calculated from the molecular mass and the mass of the radioactive compound, the disintegration constant can be obtained. From the disintegration constant the half-life is obtained by

$$T = 0.693/\lambda$$

It is very difficult to determine the total number of disintegrations per second with a G-M tube, because the normal G-M tube will not record all the disintegrations or ejected particles. If a thick film of radioactive material is prepared, a substantial portion of rays are absorbed in passing through the upper portion of the layer. If the layer is made sufficiently thin, the number of rays absorbed in the material, referred to as self-absorption, is decreased. Thus, extremely thin layers of material are deposited on surfaces in order to increase the accuracy of the reading.

If such a sample is placed at the window end of a thin window G-M counter, it would seem that exactly half of the rays, those that are traveling toward the window, would be counted by the G-M counter. This is not strictly true, however, because some rays traveling in the opposite direction or away from the tube are reflected by the backing material into the tube. This is a function of the thickness and by the mass of the material used for the backing. For this reason, an extremely thin metallic plate is used and an extremely thin film of the nuclide is deposited on the backing in order to yield more accurate results.

A third source of error is encountered when some of the rays are absorbed by either the air or the window of the G-M tube itself and do not reach the sensitive portion of the counter. A special G-M counter constructed so that the sample is inside the G-M counter itself rather than on the outside of the window solves this problem. Counters have been designed so that the radioactive material in the form of a gas can be introduced into the counter itself. Except for the layer of material very close to the wall of the counter, such devices count all of the radioactive disintegrations in the tube.

Gamma rays produce so slight an ionization that not all of the gamma rays passing through a G-M tube produce enough ionization to initiate the electrical discharge that operates the counter. Thus, great care must be taken that the counter is sensitive only to such phenomena that produces one ray for each disintegration in order to accurately measure the total number of disintegrations produced by the material under study. A further complication arises from the fact that the G-M counter itself is not continuously sensitive and that corrections for coincident counts must be made.

Fortunately, these considerations are not involved in a determination of the half-life of an element by direct methods or in the determination of the disintegration constant from such a half-life. The ratio of gamma rays to disintegrations and the efficiency of the counts remain constant for gamma rays so that the activity for gamma rays may be noted on successive days in arriving at the half-life for the nuclide.

QUESTIONS

1. Define the half-life of a radioactive element.
2. What is the half-life of a stable element?

3. If the disintegration of a particular atom is a function of probability, why is the half-live a constant?
4. Calculate the activity at the end of ten half-lives in percent of the initial activity.
5. Calculate the disintegration constant λ for a radioactive element having a half-life of 25 years.
6. For the element in Problem 5, calculate the number of disintegrations per minute if the total number of radioactive elements equals 3×10^{18}. (Note that in the preceding two problems all units of time must be converted to seconds for use in the equations.)
7. Uranium-238 decays into uranium-234 by emitting first an alpha particle and then two successive beta particles. The half-life of uranium-234 is 2.48×10^5 years and for uranium-238 it is 4.51×10^9 years. Samples found in nature are in equilibrium, that is, the rate of decay of uranium-238 is equal to the rate of decay of uranium-234. Since uranium-238 makes up 99.274 percent and uranium-234 0.0058 percent of samples found in nature, show that the number of uranium-238 disintegrations exactly equals the number of disintegrations of uranium-234.
8. List four obvious sources of error in using the G-M counting system.
9. In spite of the errors present, why is it valid to compare two samples containing the same nuclide?
10. Why is it not valid to compare the activity of two nuclides, say, low energy beta particles from carbon-14 with high energy beta particles from phosphorus-32, using a G-M counting arrangement?
11. Is it possible to induce radioactivity into matter by high intensity gamma radiation?
12. Is it possible to induce radioactivity into matter by bombarding matter with beta rays?
13. Is it possible to induce radioactivity into matter by bombarding matter with alpha rays?
14. What simple precaution is taken to avoid contamination by induced radioactivity?

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7 absorption and self-absorption for beta rays

PLAN OF INSTRUCTION

OBJECTIVE

1. To study the behavior of beta rays and the counting rate as a function of the geometry between the beta ray source and the counter.

2. To note the absorption of beta rays between beta-ray producing material or the self-absorption of beta rays.

3. To study the effect of different types of absorbing material such as paper, aluminum, and lead.

4. To note the effect of scattering of beta rays by the absorbing material and the effect this has on the counting rate as a function of position.

5. To distinguish between hard and soft beta rays.

INTRODUCTION

1. Review the charge, energy, and mass characteristics of beta rays.

2. Review the Coulomb forces between electrical charges.

3. Review the scattering of beta rays by electrons surrounding the nucleus.

4. Review the velocity-energy characteristics of beta rays and distinguish between hard and soft beta rays.

5. Calculate the velocity of beta rays having an energy of 0.115 Mev (carbon-14) and 1.17 Mev (bismuth-110) or 1.72 Mev (phosphorus-32).

TEACHING PLAN

1. Beta particles are high velocity electrons and behave as high velocity electrons.

2. Coulomb forces produce a repulsion of the electrons as the electrons approach other electrons.

3. Beta particles react with atoms they come in contact with.

4. The reaction of beta particles and atoms produces one of a series of effects:
   a. Elastic collision with the electrons orbiting about the nucleus resulting in a change in direction
   b. Beta particles share a portion of their energy with atoms with which they have collided, resulting in a decrease in energy of the beta particles.

   c. If the thickness of the absorbing material is sufficiently great, the beta particle is slowed down completely and results in one excess negative charge.
   d. Absorbed beta particles produce heat in the absorbing medium and add a negative charge to the absorbing matter equal to the charge of the electron.

5. The range of the beta particle is given in terms of the absorbing material calculated in mg/cm^2.

6. Beta particles are both absorbed and scattered by an absorbing layer in the path of the beta particle.

7. The range of beta particles is a function of the energy of the particle.

8. The range expressed in mg/cm^2 is not a strong function of Z, the atomic number of the absorber.

9. The intensity of beta particles transmitted through an absorber varies exponentially with the thickness of the absorbing material and is measured in mg/cm^2.

10. To measure the total number of beta particles being emitted by matter, it is necessary to account for absorbers due to:

    a. The layer of matter between the radiating nuclei and the top of the layer.
    b. The air between the radioactive matter and the G-M counter.
    c. The thickness of the window of the G-M counter.

APPARATUS

G-M tube with rack to hold tube and sample

G-M scaler with variable voltage control

Timing system, such as timer or clock

Phosphorus-32, 5 ml, 10 μc (Nuclear-Chicago RCB-1)

or

Bismuth-210, also known as RaE (Atomic Accessories, Inc., No. SCB-1225-6)

Ten cardboard absorbers, ten aluminum absorbers, and ten lead absorbers to fit the G-M tube holder

EXPERIMENTAL PROCEDURE

1. Arrange the apparatus as shown in Fig. 7-1.

2. Prepare a planchet by transferring 0.1 ml of phosphorus-32 to the planchet and evaporating the water with a sun lamp.

3. While the planchet is drying, turn on the G-M counter and take a minimum of five one-minute readings of the background count with an identical planchet in place in the counting arrangement.

4. Place the prepared planchet on the holder approximately one inch from the window of the G-M tube. Great care must be exercised to assure that the mica window of the end-window counter is not damaged.

5. Take a series of five one-minute readings of the activity. Samples of phosphorus-32 will vary in activity. If the counting rate is less than 5,000 counts per minute, increase the quantity of radioactive material until this counting rate is reached. The planchet may be moved closer to the G-M tube, but space should be left for the absorbing material.

6. Place one aluminum plate between the source and the G-M tube and take a series of five one-minute readings. Subtract the background count from each reading, preferably by removing the radioactive planchet while leaving the absorbing aluminum plate in position. Repeat the process by adding 2, 3, 4, 5, and 6 absorbing plates or until the activity recorded in counts per minute has dropped to 1/10th the original count.

7. Determine the mg/cm^2 for aluminum by weighing the plates and dividing the mass in grams by the area of the plate in square centimeters.

8. Plot the activity in counts per minute against the thickness of the absorber in mg/cm^2. Determine the thickness of aluminum that will reduce the activity to one-half the initial activity. This value is the half-thickness of aluminum for beta particles from this particular isotope. Is this a function of the energy of the beta particle?

9. Make one reading with a thickness of lead and one reading with a thickness of cardboard. Determine the mg/cm^2 for the lead absorber and the cardboard absorber and plot the points on the graph paper. The points thus plotted should fall very close to the curve obtained for aluminum.

10. Calculate the error introduced by disregarding the thickness of the mica end-window and the air between the sample and the G-M tube. Note that if a glass-walled tube with a wall thickness of 30 mg/cm^2 is used, the total readings are materially altered, but the half-thickness of aluminum does not change.

11. Remove all of the absorbers and take a set of readings, first with a single aluminum absorber as close to the planchet as possible, and second with the absorber as close to the end-window of the G-M tube as possible. Why is there a difference in the two readings? It will be noted that the discrepancy will be larger if the separation between the radioactive sample and the G-M tube is increased.

12. Plot the activity versus mg/cm^2 on semi-log paper and note that the resulting curve is a straight line. This representation is useful for extrapolating or obtaining the actual count from a series of counts through absorbers. The curve is extended to the left of the zero line an amount equal to the thickness expressed in mg/cm^2 of the cover plate (if used), the air path, and the thickness of the G-M tube.

RESOURCE MATERIAL

Many practical applications of nucleonics are based upon an accurate measurement of the radioactivity produced by beta particles. This experiment and the following experiment are concerned with the considerations that must be given to radioactivity measurement of beta particles.

The general arrangement of the experiment is as indicated in Fig. 7-1. In this experiment only self-absorption, absorption of the cover, absorption in air, absorption in the G-M tube window, and scattering of the beam by the absorbing material will be considered.

Since the emission of beta particles is distributed randomly in space, the total number of particles arriving at the window of a G-M tube from a point source in a vacuum would follow the inverse square law. This means that if the distance from the sample to the counter tube were doubled, the number of rays reaching the G-M tube would be reduced to one-fourth.

If the sample is distributed over an area that is large compared to the diameter of the counter tube and if the separation between the sample and the counter tube is small compared to the area of the sample, the radiation is independent of the distance between the sample and the counter tube.

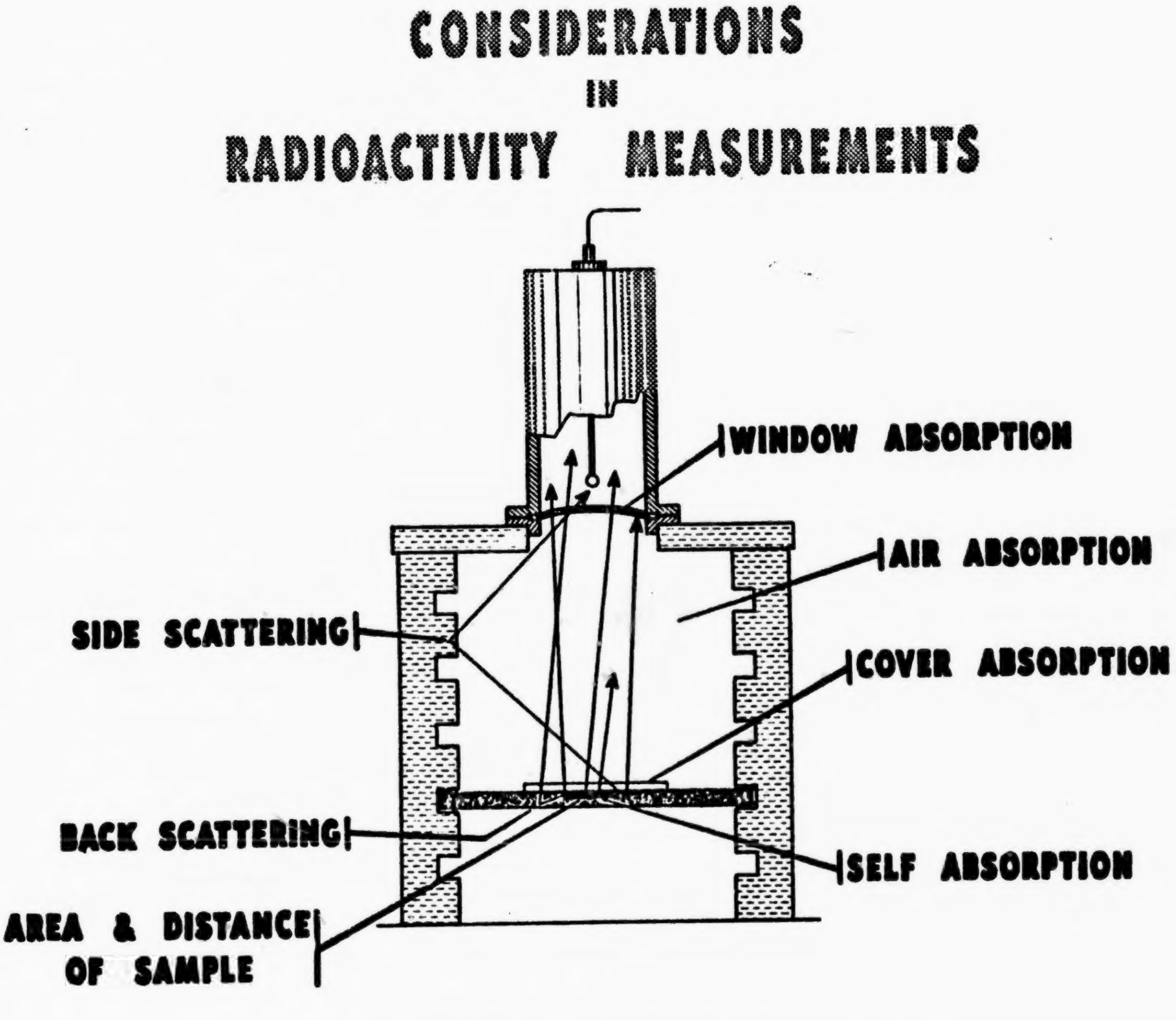

CONSIDERATIONS
IN
RADIOACTIVITY MEASUREMENTS
WINDOW ABSORPTION
AIR ABSORPTION
SIDE SCATTERING
COVER ABSORPTION
BACK SCATTERING
SELF ABSORPTION
AREA & DISTANCE OF SAMPLE

Fig. 7-1. End-window G-M tube and sample holder

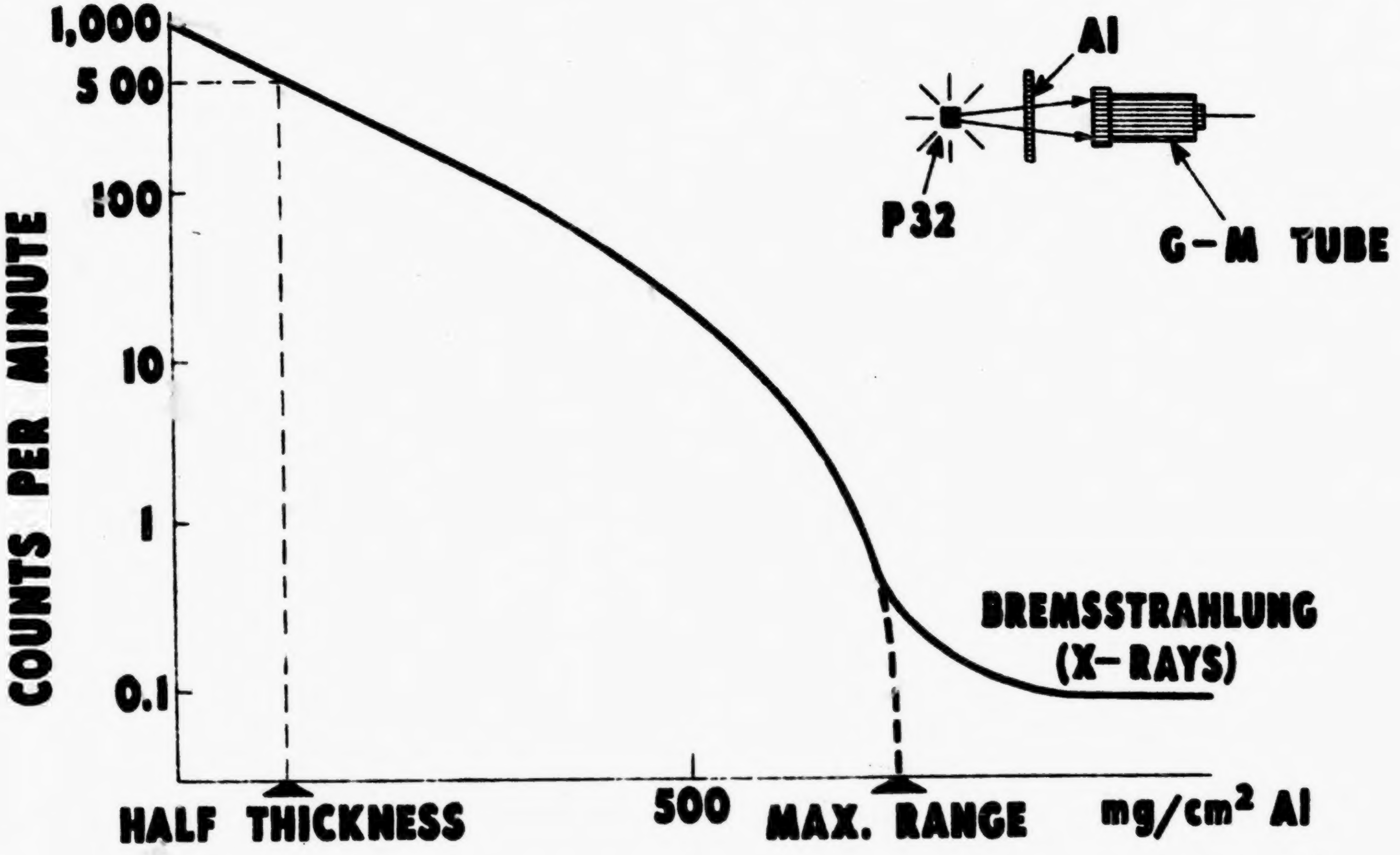
Neither of the above cases is achieved in practice, and it is common to find the sample distributed over an area having a diameter of approximately one inch and to find end-window G-M tubes used as counters having approximately the same diameters. Furthermore, the sample may be from one to five inches from the counter window.

Beta particles are identical to high velocity electrons and are emitted by the nucleus when a neutron is converted into a proton. Velocities of beta particles from carbon-14, for example, are equal to velocities electrons would acquire if they were accelerated by 0.115 Mev. Those from bismuth-210 have an energy of 1.17 Mev. In addition, not all beta particles from the same nuclide have identical energy. Rather, they have a range of energy. Beta particles obey the laws of forces relating to electrical particles.

The force in dynes between two charged particles is equal to the magnitude of the charge in esu units divided by the distance squared in centimeters and is written

$$F = \frac{-e_1e_2}{d^2}$$

RANGE OF BETA PARTICLES



P 32 β PARTICLES IN ALUMINUM

. ABSORPTION IS PRACTICALLY EXPONENTIAL AT START

. MAXIMUM RANGE USUALLY 7 OR 8 TIMES ½ THICKNESS

When a beta particle is emitted from a nuclide, it travels in a straight line until it approaches an atom. The Coulomb forces between the charge on the beta particle and the charge on the electrons surrounding the atom are in such a direction to produce a repulsion force. Consequently, the beta particle is repelled by the atom. Furthermore, since the beta particle is light in comparison with the atom it encounters, the particle is deflected. In the interaction corresponding to the conditions of Newton's third law, some energy is imparted to the atom, and the atom acquires a velocity that is inversely proportional to the mass of the interacting particles. Since the atom acquires some velocity, it also carries away with it some of the original energy of the beta particle. As a result, the beta particle is slowed down. A beta particle interacts with electrons around the nucleus of an atom while still a great distance from that atom. As a consequence, a beta particle continually loses energy to atoms in its path, even in the case of a particle traveling through air.

Beta particles may react with atoms that are part of a solid. The range of beta particles is defined in terms of the mass of matter penetrated rather than the distance as is the case for alpha particles. Specifically, the range of beta particles is defined as the penetration in terms of mg/cm^2. Since the mass of matter increases with atomic number and since the number of atoms per cubic centimeter in a solid remains somewhat constant, the range expressed in mg/cm^2 is not a strong function of the atomic number of the absorber. Thus, the range calculated for air, cardboard, mica, aluminum, and copper will be roughly the same.

The range, however, is a function of the energy of the beta ray. For energies above 0.5 Mev, the range is nearly a linear function and is given as

$$R(mg/cm^2 \text{ of Al}) = 520\ E_m\ (\text{Mev})\ -90$$

To the first approximation, this equation can be used to calculate the range of mica, air, and other absorbing material.

In the case of the practical determination of counts by means of an absorber, it is thus possible to determine the range by adding together the range in mg/cm^2 of the cover, the air, the mica window, and the absorbers that are placed between the nuclide and the G-M tube. The thickness of the window in the probe is usually specified by the manufacturer. Typical glass windows are 30 mg/cm^2, mica windows designed for carbon-14 counting are from 1 to 2 mg/cm^2, and general purpose end-windows for hard beta particles are from 3 to 4 mg/cm^2. The factor to be used for air is 1.3 times the distance in centimeters of air from the top of the sample to the probe. This is the mass of air in the 1 cm^2 column of air in question.

If the absorbing material is placed between the radioactive source and the counter window, the total number of counts observed varies as shown in Fig. 7-2, a graph of the activity in counts per minute as a function of aluminum absorbers having a thickness of 24 mg/cm^2. Successive readings are shown with 1 to 3, 4, 5, 6, and 7 aluminum plates. The effect of air and the window in the G-M tube are not considered. In order to arrive at a more accurate count, the curve must be extrapolated to the left side to an amount equal to the range for the air and the window.

If the beta particles arriving at the counter tube are in a well-defined beam, the position of the absorber has a definite effect on the number of beta particles recorded by the counter. If the absorber is close to the window, the particles that suffer elastic collision and are deflected may still enter the G-M tube. If, however, the absorber is far away from the window, beta particles that are severely deflected may miss the G-M tube altogether and not be counted. The counting rate, therefore, decreases as the absorber is moved further away from the G-M tube.

Since the G-M counter is sensitive to gamma rays as well as beta particles, care must be exercised that the radioactive sample emits only beta rays (A list of useful radioactive isotopes together with the half-life, beta particle energy, and gamma emission is given in Nuclear Radiation Physics). Among the readily available beta emitters that do not emit gamma rays are bismuth-210, calcium-45, iron-55, phosphorus-32, silver-111, and sulfur-35. For the purpose of this experiment, phosphorus-32 is probably the most desirable sample. With a phosphorus-32 nuclide it is possible to observe self-absorption by the layers of the sample through which beta rays must pass in order to reach the G-M counter.

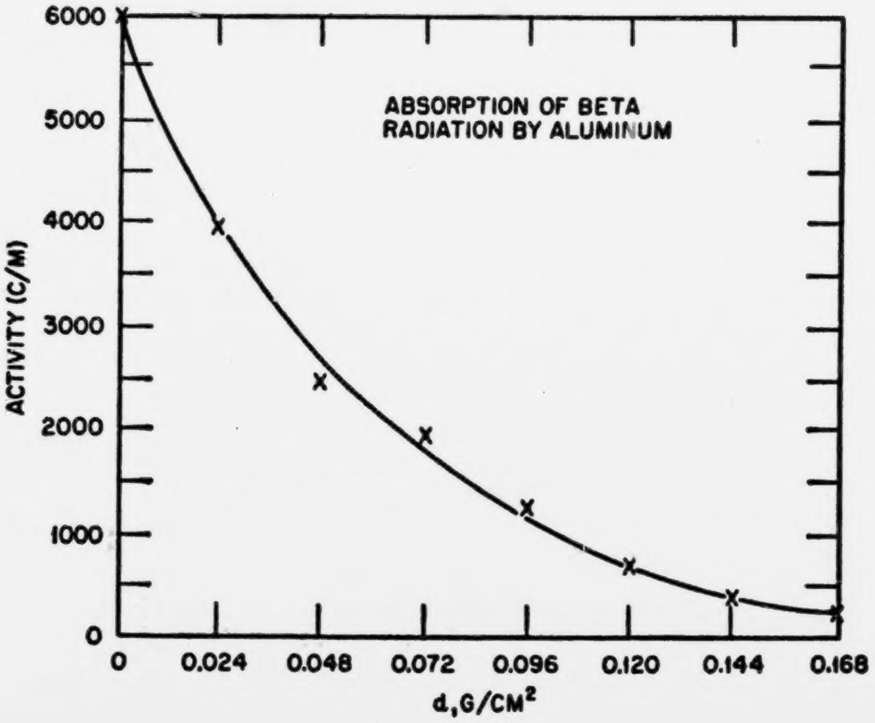


Fig. 7-2. Activity as a function of the number of absorbers, d = 24 mg/cm^2

The phase of the experiment dealing with self-absorption is performed by placing 0.1 ml of phosphorus-32 on a planchet, evaporating the liquid, and making a series of counts, which are recorded. An additional 0.1 ml of phosphorus-32 is then placed on top of the original deposit, evaporated, and counted. Repeated additions of phosphorus-32 are added and the counting rate is noted.

Were there no self-absorption, the counting rate would increase uniformly with each additional 0.1 ml of the radioactive isotope. A point is reached, however, where additional layers of the radioactive material have less and less effect on the count. If the layer is sufficiently thick, a saturation count is reached. At this point all of the beta particles from the lower layers are absorbed or deflected.

QUESTIONS

1. Describe the phenomenon of absorption of beta rays.
2. Calculate the force on a beta particle as it approaches within 5 x 10^{-12} cm from the nucleus of the gold atom, Z = 97.
3. What is the meaning of half-thickness for an absorber used with beta particles?
4. Calculate the thickness in mg/cm^2 for a 1/32-inch thick sheet of aluminum whose density is 2.7.
5. Calculate the mg/cm^2 for a column of air 10 cm long.
6. If the maximum range of beta particles is approximately eight times the half-thickness, what is the range in centimeters for aluminum when the half-thickness is 20 mg/cm^2?
7. Bremsstrahlung X rays are produced when beta particles react with the electron rings of an atom. Such rays are recorded by a G-M tube. How will this affect the activity versus mg/cm^2 in this experiment?

8. What would be the effect of using a nuclide that emits gamma rays as well as beta rays in this experiment?
9. Suggest an experimental set-up that would permit the use of a nuclide emitting both gamma and beta rays.

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8 backscattering and other effects for beta rays

PLAN OF INSTRUCTION

OBJECTIVE

1. To study the scattering of beta rays by the planchet on which the beta ray source is placed.

2. To study the observed beta ray activity as a function of the thickness of the metals beneath the radioactive source.

3. To note the variation in observed beta ray activity as a function of the thickness and the atomic weight of the metal beneath the radioactive source.

4. To observe the effect of side scatter on the counting rate.

5. To observe the back and side scatter as a function of the energy of the beta ray.

INTRODUCTION

1. Review the absorption of beta rays by absorbing media between the radioactive source and the G-M counter.

2. Review the thickness unit, expressed in mg/cm^2, which is used for correlating the effect of different substances to the observed counting rate.

3. Review the scattering of the beam of beta particles as the result of particles passing close to atoms.

TEACHING PLAN

1. Beta particles are emitted from the nucleus and distributed at random in space.

2. Equal numbers of beta particles are initially moving away from and toward the counter tube during the experiment.

3. Those particles that are moving away from the counter tube may be deflected toward the tube if they encounter an atom. This is referred to as elastic scattering and depends on the number of electrons surrounding the atom.

4. Coulomb forces exist primarily between the electron shells and the beta particle. Thus, an atom with a large atomic number has a large number of electrons surrounding the nucleus and exerts a larger force on the beta particle than an atom with a small atomic number.

5. Many beta particles are scattered by interaction with one or more atoms and may have multiple interactions with atoms.

6. The observed counts produced by a system increases as the thickness of the backing material increases and eventually reaches a maximum or saturation point.

7. Saturation backscattering is independent of the maximum energy of the beta particle for energies above 0.3 Mev.

8. Side scatter can be employed to contain the beam and thus increase the observed counting rate.

9. The same characteristics that affect backscatter are applicable to side scatter.

APPARATUS

G-M tube with rack to hold tube and sample

G-M scaler with variable voltage control

Timing system such as timer or clock

Phosphorus-32, 5 milliliters, 10 microcuries (Nuclear-Chicago RCB-1)

or

Bismuth-210, also known as RaE (Atomic Accessories, Inc., No. SCB-1225-6)

Ten cardboard absorbers, ten aluminum absorbers, and ten lead absorbers to fit the G-M tube holder

Carbon-14 (Nuclear-Chicago No. R5 or similar)

EXPERIMENTAL PROCEDURE

1. Deposit 0.1 ml of phosphorus-32 on a piece of filter paper and dry the paper under a sunlamp.

2. Record the background counts by making a standard series of five one-minute counts of the background.

3. Mount the filter paper in the G-M tube and sample holder in such a manner that there is no metallic backing behind the radioactive sample.

4. Place the radioactive source on an aluminum plate and determine the counting rate with the backing.

5. Repeat the above with 2, 3, 4, 5, and 6 plates, keeping the distance from the radioactive sample to the G-M tube constant.

6. Repeat the procedure with some other heavy backing material, such as gold or lead.

7. Plot the backscattering curve as a function of the counts per minute against the mg/cm^2 of the two backing materials used.

8. Determine the thickness of backing material in mg/cm^2 that produces a saturation backscatter effect. Correlate this to the absorption half-thickness factor in the previous experiment.

9. Surround the space between the sample and the G-M tube with a cylinder of reflecting material such as cardboard, aluminum, or lead and observe the resulting counts.

RESOURCE MATERIAL

In addition to the effect of the absorption of rays by the material interposed between the sample and the G-M tube, it is necessary to consider the effects produced by elastic scattering (Rutherford scattering). If a beta particle is emitted initially traveling in a direction away from the G-M tube, it may experience multiple scattering in the backing material, emerge in the opposite direction, and enter the counting tube. This phenomenon is known as backscatter.

The rate of the observed counts varies as a function of the initial energy of the beta particle and the atomic number of the backing material. If the thickness of the backing is increased, the rate of observed counts likewise increases up to the point of saturation. This point is referred to as saturation backscattering. With sufficient thickness of the scattering material, the backscatter factor is independent of the initial energy of the beta particle.

Backscattering factor f_B is defined as the ratio of the counts with backing material to the counts without backing material. If this ratio is plotted against the thickness of the backing material in mg/cm^2, the backscatter factor increases as the thickness of the backing material is increased. The increase is faster with increasing backing thickness for the lower energy beta particles. For beta particles having an energy greater than 0.3 Mev, saturation values are found to be independent of the energy of the particle.

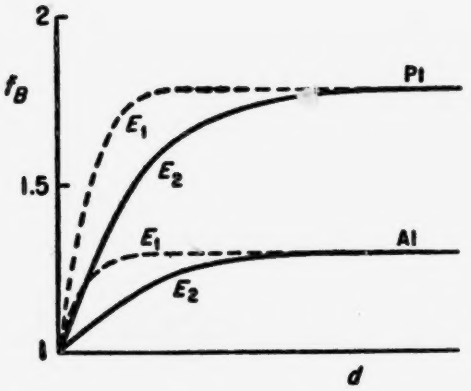


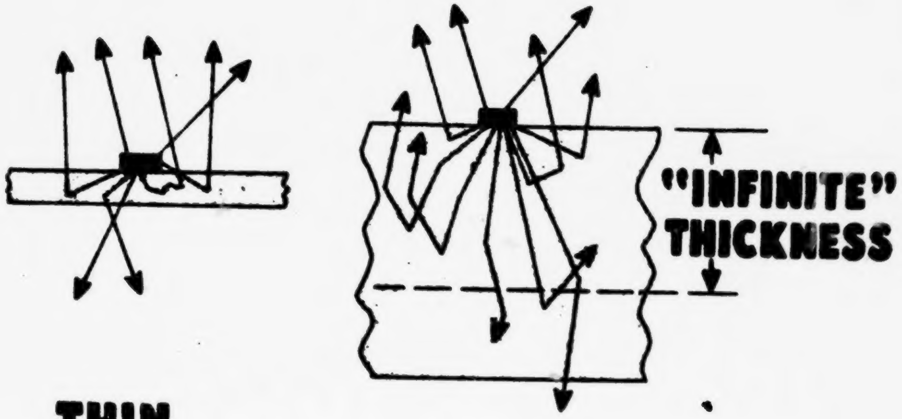
Fig. 8-1. The effect of backscatter as a function of the mg/cm^2 for Al and Pt for two values of energy. (From Experimental Nucleonics by Ernst Bleuler and G. Goldsmith. Copyright 1952. Holt, Rinehart and Winston, Inc., New York. Used by permission.)

Table 8-1
SATURATION BACKSCATTERING FACTORS

Backing	Z	f_B^S		
		(a)[1]	(a)[3]	(b)[3]
Lucite	—	1.15	—	—
Cardboard	—	1.19	—	—
Al	13	1.29	1.20	1.33
Fe	26	—	—	1.59
Cu	29	1.48	1.43	—
Ag–Pd	46–47	1.66	1.59	1.83
Pt	78	1.78	—	—
Pb	82	—	1.74	2.05

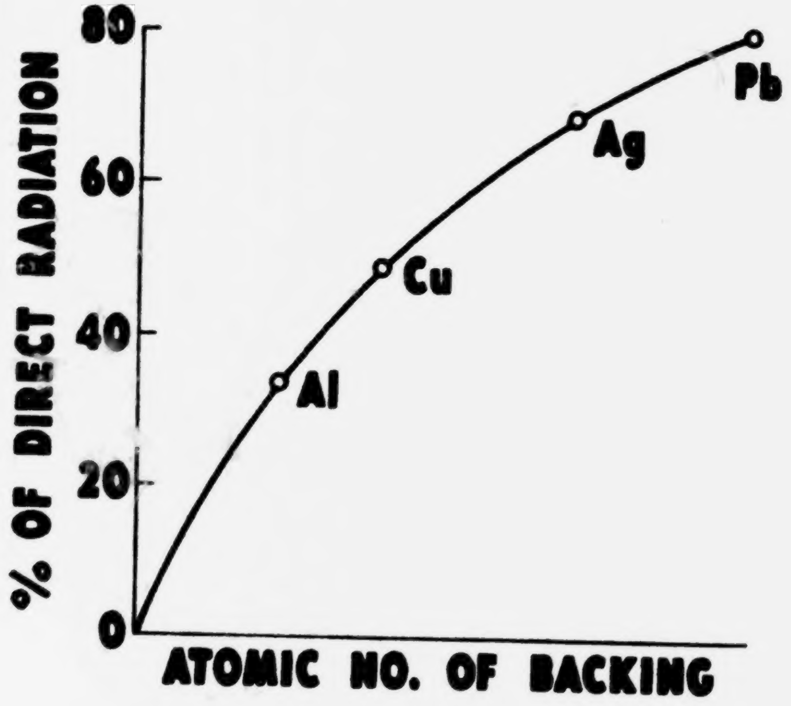
(From Experimental Nucleonics by Ernst Bleuler and G. Goldsmith. Copyright 1952. Holt, Rinehart and Winston, Inc., New York. Used by Permission.)

BACKSCATTERING OF BETA PARTICLES



THIN BACKING

THICK BACKING



EXTENT OF "SATURATION" BACKSCATTERING

- BACKSCATTERING INCREASES WITH THICKNESS
- "SATURATION" OCCURS AT "INFINITE THICKNESS" (APPROX. ½ MAX. RANGE)

Backscattering, however, is directly related to the atomic number Z and the number of electron shells around the nucleus. With no backing, the backscatter factor f_B is unity. If backing material is added, the observed counting rate will increase to some point approximately equal to 2 for the largest atomic numbers. Fig. 8-1 illustrates the effect of backscatter as a function of the mg/cm^2, the increasing atomic number, and the two levels of energy of beta particles.

Table 8-1 illustrates the dependence of saturation backscattering on the atomic number Z. It will be noted that the elements with low atomic numbers produce a 25 percent increase in the counting rate. Elements with the larger atomic numbers produce an increase of over 75 percent.

The thickness of the material producing saturation backscattering is also a function of the mg/cm^2 and is approximately equal to 0.2R, where R is the maximum range of the beta particle in the particular absorber as defined in Experiment 7.

The same general conditions apply to cases of beta particles that are emitted in a direction missing the window of the G-M tube. It is possible to simultaneously shield the tube from external radiation and to increase the radiation from the source under investigation by placing a shield around the tube and enclosing the source. As in backscattering, the effectiveness of the shield increases until the thickness is equal to about one-half the range R of the beta particle. Again a practical maximum is reached for

$$d = 0.2R$$

where d is measured in mg/cm^2.

It is important to understand that in addition to providing shielding from external sources and for increasing the observed counting rate of a sample, an understanding of backscattering and side scattering will emphasize the need for uniform conditions when carrying out reliable counting experiments.

In performing this experiment, it is desirable to deposit the initial radioactive sample on a very thin backing so that essentially no back scattering occurs. This sample may then be placed upon various thicknesses of backing material and various types of backing material to observe the backscatter effect. In those cases where an incapsulated sample is used, care should be taken to select a sample that has the very lightest backing. The experiment may be repeated with low energy beta particles by using beta particles from carbon-14, 0.155 Mev. Phosphorus-32 emits beta particles with an energy of 1.72 Mev. Both isotopes are obtainable in liquid form in order to prepare samples on blotting paper.

QUESTIONS

1. Describe the phenomenon of backscattering by considering the charge on a beta particle and rings of negatively charged electrons around an atom.
2. What part does absorption play in the phenomenon of backscattering?
3. On the basis of the number of electrons around each atom, how is the increased efficiency of backscattering explained as the atomic number increases?
4. What geometrical considerations must be made so that counts on successive samples will be valid?
5. Define the backscattering factor f_B.
6. Why is it not possible for the backscattering factor to exceed 2?
7. What is meant by saturation backscattering?
8. How does the backscattering factor f_B vary with the atomic number?
9. If the backing material remains constant, how does the backscattering vary as the energy of the beta particle increases?

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9 absorption and inverse square law for gamma rays

PLAN OF INSTRUCTION

OBJECTIVE

1. To show experimentally that the intensity of gamma radiation varies inversely with the square of the distance from the source.
2. To study the effect of a point source of gamma radiation and compare it with an extended source.
3. To show the similarity between gamma radiation and X-ray radiation.
4. To review the unit used to measure gamma and X-ray radiation, the roentgen.
5. To describe the phenomenon of the absorption of gamma rays.
6. To determine the half-thickness layer of shielding by experimental methods.

INTRODUCTION

1. Review the units previously defined to measure X-ray radiation and gamma radiation.
2. Review the tolerance for X-ray and gamma radiation as previously defined.
3. Review the type of rays given off by radioactive isotopes.

TEACHING PLAN

1. Gamma and X rays of a given energy have identical properties.
2. Gamma radiation occurs as part of the radiation produced by the disintegration of a radioactive nucleus; X-ray radiation is produced when a high velocity electron impinges on an atom.
3. Gamma radiation produces a minimum of ionization. Consequently, the range or distance that the gamma ray travels is very large, approximately 10,000 times the range of alpha particles and 100 times the range of beta particles.
4. Gamma rays are never completely absorbed; the intensity of the radiation is decreased in passing through matter. The probability of one of the absorbing phenomena taking place is proportional to the intensity of the radiation.
5. The processes mainly responsible for the absorption of gamma rays are
    a. Compton's scattering by the electrons of the atom wherein the gamma ray is deflected and an electron is ejected from the electron shell around an atom.
    b. The phenomenon of pair production of electrons and positrons as the interaction takes place between gamma rays and the electric field of the atomic nuclei.
    c. Photoelectric absorption by the atom.

6. The intensity of the gamma ray emerging from an absorber varies as an exponential function dependent upon the thickness of the absorber.

7. A convenient way to describe the effect of the absorber is to define the effectiveness of the absorber in terms of half-thickness--the thickness that reduces the intensity of gamma radiation to one-half the original intensity. Subsequent half-thickness layers reduce the intensity to 1/4, 1/8, 1/16, 1/32, 1/64, etc., of the original intensity. Seven half-thicknesses reduce the radiation to less than 1 percent of the original.

8. In the absence of absorbers, gamma radiation is emitted with random orientation in space, and the intensity in any direction from a point source is uniform.

9. The intensity of radiation follows the inverse square law; as the distance doubles the intensity is reduced to one-half.

10. The absorption of gamma radiation in air is so slight that the decrease in radiation from a source is determined primarily by the inverse square law.

APPARATUS

G-M tube with rack to hold tube and radioactive sample

G-M scaler with variable voltage control

Timing system, such as a timer or clock

Vial of iodine-131 as potassium iodide, 5 ml, 10 μc (Nuclear-Chicago No. RCB-1)

A set of lead plates approximately 1/32 inches thick

A meter stick

EXPERIMENTAL PROCEDURE

Inverse Square Law

1. Allow the counter to warm up and adjust the voltage to the lower portion of the counting plateau.

2. In order to prevent beta particles from reaching the G-M tube, leave the iodine-131 sample in the closed bottle and shield the vial with a 10 mil thickness layer of aluminum. G-M tubes that are equipped with a beta shield may be adjusted so that the shield prevents beta particles from reaching the tube.

3. Bring the vial close enough so that the counting rate is in the vicinity of 5,000 counts per minute. Record the counts and the separation distance between the center of the counter and the center of the vial.

4. Remove the vial away from the G-M counter by doubling the separation distance and make a series of readings with the distance 2, 3, 4, and 5 times the initial spacing.

5. Subtract the background count from the observed counting rate to get the corrected rate for the gamma radiation.

6. Plot activity versus separation in units of the initial separation. The activity can be plotted in terms of percentage of activity compared to the initial activity. The curve should be the typical inverse square curve.

Absorption of Gamma Radiation

1. Place the vial of iodine-131 close enough to the G-M tube so that the activity is in excess of 5,000 counts per minute.
2. Recheck the background count and determine the net activity.
3. Interpose one lead absorbing plate between the sample and the G-M tube by placing the absorber as close to the G-M tube as possible.
4. Record the activity for a series of readings by interposing additional lead absorbing plates.
5. Continue adding lead plates until the activity has decreased to 10 percent of the initial activity.
6. Subtract the background counts from each reading and plot the activity as a function of the number of absorbers.
7. Determine the thickness of lead required to reduce the gamma ray activity to one-half the initial activity.
8. The maximum gamma ray energy for iodine-131 is 0.638 Mev, and the half-thickness should be found to be close to 0.33 inches.

RESOURCE MATERIAL

Gamma rays were discovered after the behavior of X rays had been studied. Since the energy of the gamma radiation was so much more intense than any then available X-ray radiation, it was believed that gamma radiation was a different type of radiation. Subsequent improvement of X-ray equipment has resulted in X-ray energies that far exceed the available energy from radioactive gamma sources. It has further been possible to show that the two types of radiation with a given energy are identical, one produced from a radioactive source and the other from the interaction of an electron and the innermost electron shells in an atom.

Gamma rays do not have specific or discreet ranges or energies as are found for alpha particles. Unlike alpha and beta particles, where energy is lost in a large series of elastic collisions with other atoms, the energy loss in gamma rays is of a "one-shot" nature. The total energy of the gamma ray is lost in a single interaction with an atom. This nature of the removal of energy of the gamma ray results in an exponential absorption phenomenon. The intensity of the radiation, when plotted, is similar to that of the half-life curve.

Gamma radiation is contained in discreet quantities, called photons, and the energy of the photon is given by

$$\text{Energy} = h\gamma$$

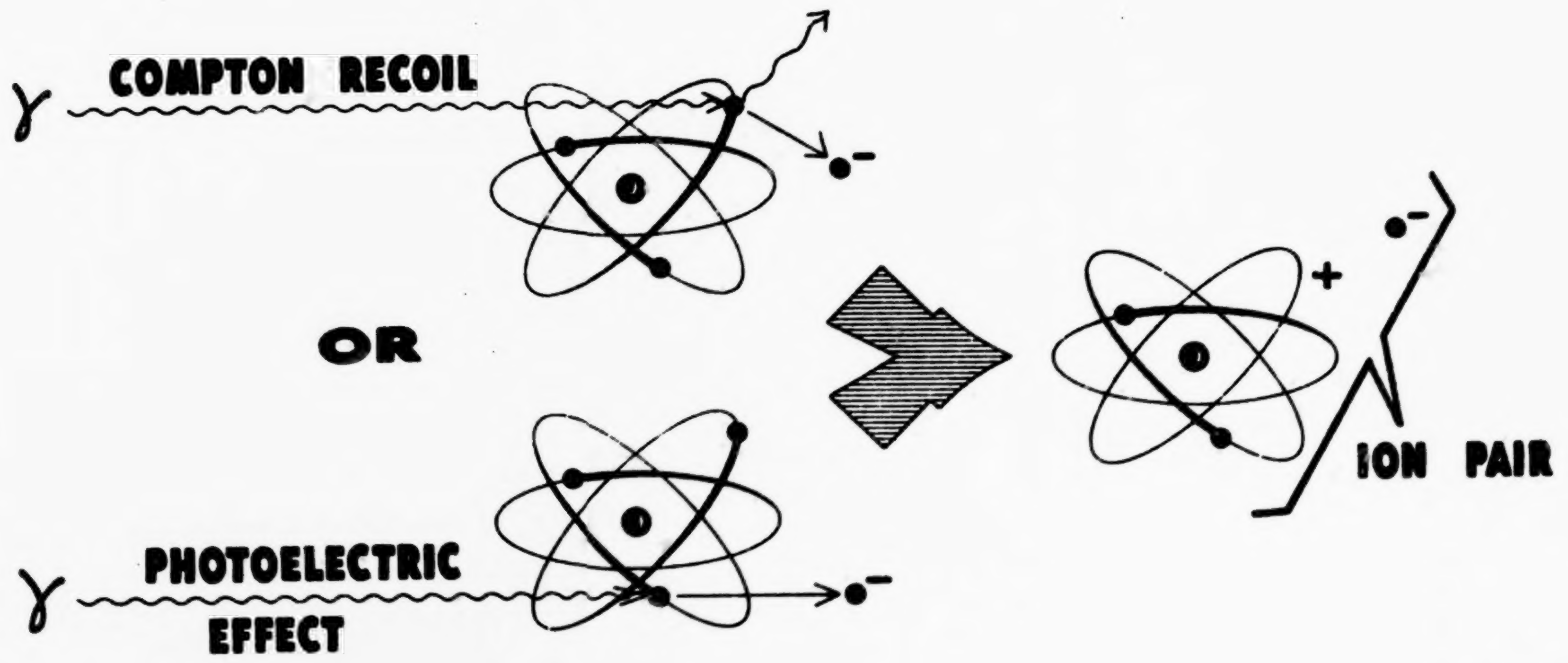
where h is Plank's constant and γ is the frequency of the radiating particle.

There are three processes by which the energy of gamma radiation is absorbed by atoms: photoelectric absorption, Compton scattering, and pair production.

In photoelectric absorption, the energy of the photon of gamma radiation is all absorbed by an atom and imparted to a single electron. This gives the electron a kinetic energy (velocity) equal to the original energy minus the binding energy of the electron. Gamma rays with energy ranges below 0.5 Mev impart most of their energy to atoms in matter by this method.

If the energy is greater than the energy necessary to dislodge an electron from an atom, the photon may impart a portion of its energy to the electron and may be itself converted to a

IONIZATION BY GAMMA RAYS


γ
COMPTON RECOIL
OR
γ
PHOTOELECTRIC EFFECT
+
ION PAIR

ELECTRON IS EJECTED WITH ALL OR PART OF GAMMA ENERGY

IONS THEN:
- REACT CHEMICALLY WITH MATTER
- MOVE IN ELECTRIC FIELDS
- RECOMBINE — EMITTING LIGHT
- SERVE AS CONDENSATION NUCLEI

photon of lower energy (or lower frequency). This results in the production of a gamma ray that has less energy or in the production of a photon of light. When the energy of the gamma ray is higher than 0.6 Mev, this phenomenon, known as Compton scattering, is very probable. Furthermore, the probability is proportional to the number of electrons in the atom involved in the reaction and, consequently, proportional to the atomic number Z of the absorbing matter.

When the energy of the gamma ray photon is 1.02 Mev or larger, a more complex reaction is possible. If the gamma ray passes close enough to the nucleus of an atom, the gamma ray may interact with the atom in such a manner as to leave the atom completely intact and may itself be converted into an electron and a positron. This process is known as pair production. This is an example of energy being converted directly to mass, and the charges on the positive electrons and negative electrons cancel exactly. The excess energy is converted into kinetic energy and the pair acquires a velocity in this phenomenon.

The electron-positron may again combine and, consequently, be annihilated. The mass is converted again into energy in the form of a photon, thus producing a gamma ray once again. In a magnetic field, the electron and the proton may be separated. An experiment can be performed to show the production of the electron-positron pair.

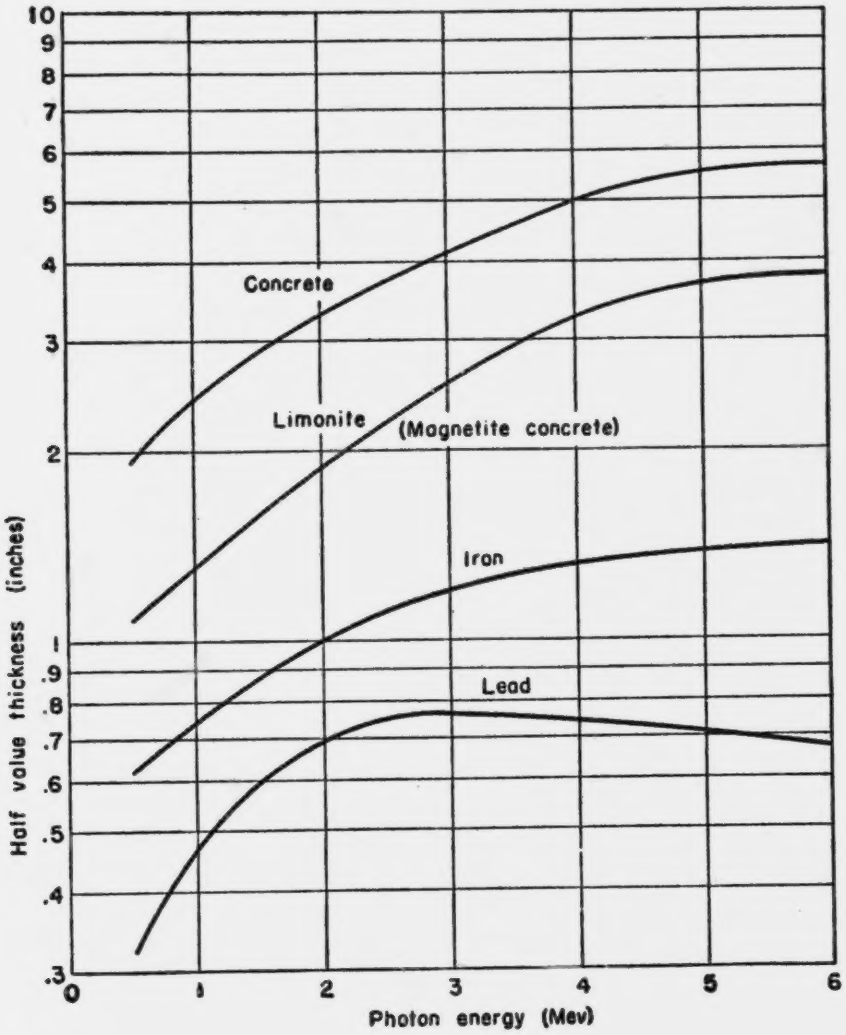


Fig. 9-1. Half-value thickness of common absorbers for gamma radiation

Understanding the concept of the half-thickness of an absorber is useful in experimentation. The thickness of an absorber will reduce the initial intensity of a photon beam to one-half in passing through the absorbing material. Since the absorption phenomena described above depend upon interaction between electrons and protons, the effect is proportional to the number of electrons in the atom and the atomic number Z. For this reason, absorbers such as lead and others high in the atomic table are most satisfactory; light elements such as aluminum are ineffective. Figure 9-1 gives the half-value thicknesses in inches for absorbers commonly used to absorb gamma rays as a function of the energy of the gamma ray.

Since beta particles are readily stopped by aluminum, aluminum or one of the lighter metals is useful in separating beta particles from gamma rays.

In an experiment to measure absorption, it is necessary that the detector is not sensitive to the electrons ejected in the phenomena described above. This can be done by placing a thin aluminum shield directly in front of the G-M tube to eliminate electrons ejected in the last absorber, yet permitting the remaining gamma rays to pass through the counter.

Any counter sensitive to gamma rays may be used in this experiment. An alternate to the G-M counting arrangement is a quartz-fiber electroscope. In general, this instrument requires higher intensity radiation than the G-M tube and, for the sake of simplicity, the G-M tube is probably preferable.

Radiation from a point source is very similar to the radiation from a point source of light because the radiation is uniform in all directions. Since air absorbs but few gamma rays, the total number appearing at a counter is essentially undiminished by absorption. Since, however, the surface area of successive spheres enclosing a point source increases as the square of the radius, the intensity of the radiation must vary as the inverse of the radius.

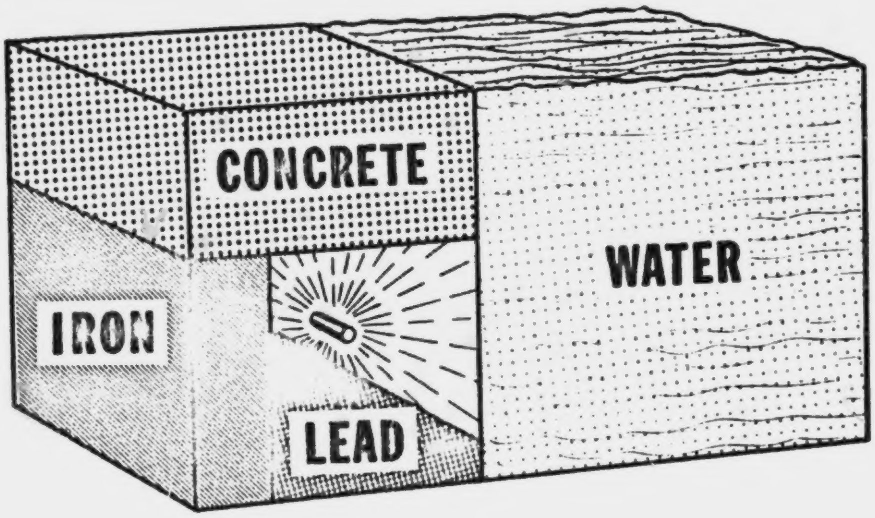


Fig. 9-2. Shielding as a protection against radiation

A series of readings made by increasing the separation between the source and the counter should consequently follow the usual inverse square law diagrammed in Fig. 9-2.

QUESTIONS

1. State the inverse law.
2. Why is it necessary to interpose the 10 mil thickness layer of aluminum between the iodine-131 sample and the G-M tube?
3. What is meant by the "one shot" nature of gamma ray absorption?
4. Define a photon.
5. What is meant by photoelectric absorption of the energy of gamma radiation?
6. Give an example of a photon of energy being converted to mass.
7. What happens when an electron and a positron combine?
8. Define the half-thickness of an absorber as applied to gamma radiation.

9. In addition to aluminum, list four effective absorbers for beta particles.
10. Arrange the following materials in order of their ability to absorb gamma radiation, listing first the most effective absorber: concrete, water, lead, iron, and hydrogen.

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10 resolving time of a g-m counter

PLAN OF INSTRUCTION

OBJECTIVE

1. To study the loss in counts recorded by the G-M counter because of the resolving time of the counter and circuit.
2. To observe on an oscilloscope the voltages produced by the counting phenomenon.
3. To determine by direct method the dead-time of the counting circuit.
4. To determine by a series of counting arrangements the resolving time of the complete circuit.

INTRODUCTION

1. Review the formation of primary ions in the G-M tube.
2. Review the formation of the avalanche of electrons produced by the initial ionization.
3. Review the action of the quenching gas in the Geiger tube with emphasis on the factors that require an elapse of time for their completion.
4. Review the necessity of electron circuits to record the counts registered by the G-M counter.

TEACHING PLAN

1. Many industrial devices utilize accurate beta counting techiques for their operation.
2. One of the unavoidable errors in beta counting is the inherent insensitivity of the counter to beta particles as a result of a previous count.
3. The period of insensitivity of the counter together with the threshold voltage necessary to activate the electronic circuit and register the count is referred to as the resolving time.
4. The resolving time depends upon the type of gas and quenching gas in the G-M counter, the characteristic of the electronic circuit, and the age of the tubes involved.
5. The resolving time of a counting arrangement must be frequently rechecked because of the aging of the tubes in the arrangement.
6. The action of the quenching gas renders the G-M tube completely insensitive to counts immediately after an avalanche has been formed in the tube and an electron sheath surrounds the center conductor of the G-M tube.
7. The high resistance in the grid circuit allows the tube to slowly recover and the voltage on the G-M tube will slowly rise to its original operating voltage.

8. A discreet period of time in the range of 100 to 200 microseconds may elapse before a pulse produced by the tube will be of sufficient height to be recorded by the electronic circuit.

9. If such a pulse occurs immediately after the tube is sensitive, the tube is again rendered insensitive for the length of time required for the tube to recover.

10. If the second pulse occurs at a period longer than the resolving time, the pulse height will increase and after the elapse of a considerable time compared to the resolving time the pulse height for a second pulse will again be the maximum.

11. The resolving time can be measured directly on an oscilloscope equipped with a time base.

12. The resolving time can be quickly measured by making two sets of counts as described in detail below.

APPARATUS

G-M tube with rack to hold tube and sample

G-M scaler with variable voltage control

Timing system, such as a timer or clock

Oscilloscope with calibrated time base or other means for measuring time intervals

Two beta sources so arranged that they may be counted separately or simultaneously by the G-M counter. A 0.2 ml sample of iodine-131 or phosphorus-32 with an activity of approximately 1 μc is satisfactory.

EXPERIMENTAL PROCEDURE

The portion of the experiment involved in making a direct determination of the resolving time by means of the oscilloscope may be used as a demonstration to illustrate the resolving time phenomenon.

1. Assemble the counting equipment, including the G-M tube and stand, together with a radioactive sample and scaling equipment.

2. Attach the oscilloscope input to the first stage of the scaling equipment. Preferably, the oscilloscope should be connected to the grid of the first tube in the scaling circuit, or it may be connected directly to the center conductor of the G-M tube through a 25 μfd capacitor. Extreme care must be taken because the potential on the center conductor of the G-M tube may rise to 1,000 volts. The coupling capacitor also must be rated for the maximum voltage on the center conductor.

3. With a radioactive sample in place, slowly increase the voltage on the counter. As the voltage reaches the proportional region, pulses will be observed on the oscilloscope but will not be recorded on the scaler.

4. Slowly increase the voltage until the first pulse registers on the scaler. This voltage is the "scaler sensitivity."

5. Increase the voltage until the pulse height no longer increases. At this point, the G-M tube is on the operating plateau. The observed pulse height should be several times the minimum pulse height for a count.

6. Set the synchronizing control so that a pulse initiates the trace. At this point, a series of traces should be observed for pulses following the initial triggering pulses,

which are similar to those shown in Fig. 10-1. It must be remembered that each of the five following pulses shown in Fig. 10-1 was the result of a separate initial pulse.

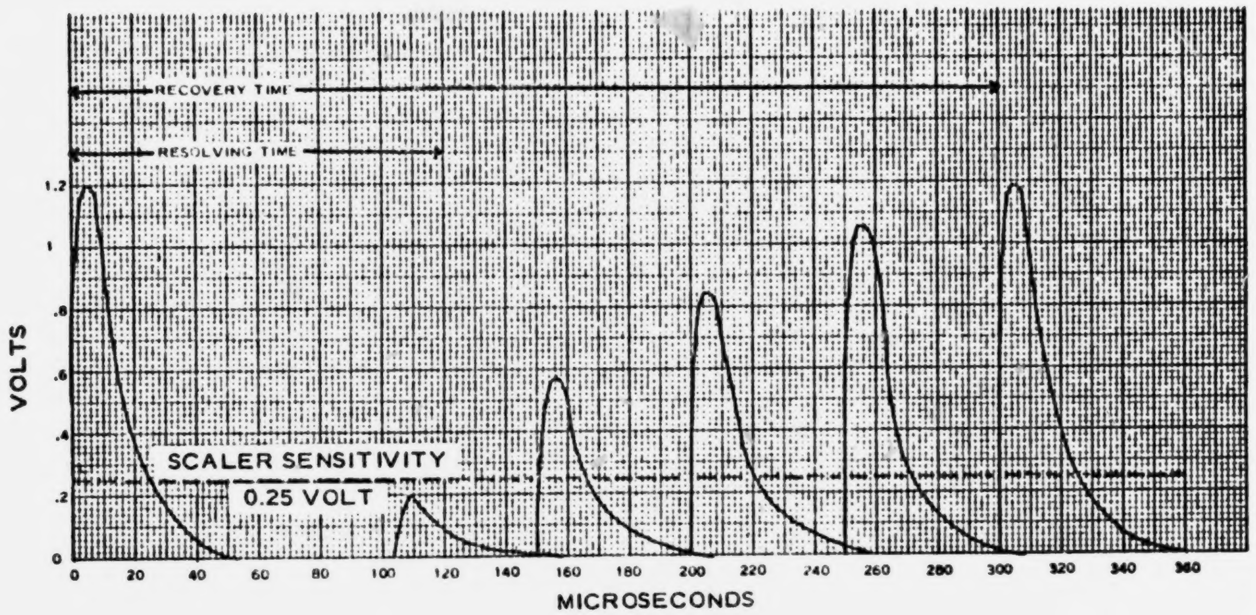

Fig. 10-1. Typical Geiger-Mueller counter pulses with mica end window and "Q" gas fill (98.3 percent He, 1.79 percent butane)

7. The resolving time can be determined by connecting the tops of the series of following pulses by a solid line. Where the resulting curve crosses the "scale sensitivity," the corresponding time is the resolving time.

The following portion of the experiment should be performed by the students:

1. Determine the background count of the counting system using a dummy planchet.
2. Arrange the first radioactive sample on the planchet, make a series of five one-minute counts, and determine the average number of observed counts.
3. Repeat the same procedure for a second sample and record the average number of counts per minute.
4. Place both samples on the planchet and determine the average number of counts for the combined samples.
5. Reduce each of the foregoing three counting rates to counts per second.
6. The resolving time can be calculated from the equation

$$t_r = \frac{n_1 + n_2 - n_{12}}{2n_1n_2}$$

where n_1 is the counting rate in counts per second for the first sample corrected for background count, n_2 is the similar counting rate for the second sample, and n_1n_2 is the corrected counting rate for the two samples counted simultaneously.

RESOURCE MATERIAL

Many industrial applications for use of radioactive materials are based on an accurate determination of the radioactivity by means of a G-M tube arranged to count beta particles. In order to accurately determine the beta activity of a radioactive sample, it is necessary to make several corrections to the apparent counting rate. Some of these corrections are easily understood when it is remembered that the tube only counts rays originating in the sample and rays that reach the G-M tube. Several corrections must also be made that are not so obvious. One of the important corrections is referred to as the correction for coincident counts or a correction to take care of the resolving time of the counter and associated electronic equipment. The corrections described in this experiment are not applicable to ionization chamber type counters, which measure total ionization, or counters that are based on the discharge of a charged electroscope.

The standard G-M counter employs argon or helium gas to amplify ionization. When such a tube is operated above the Geiger region, or on the counting plateau, a single electron produces the same ultimate electron avalanche that is produced by high ionizing rays. The signal in such an operation is due primarily to the electron amplification phenomenon in the gas. Such tubes, however, require a built-in auxiliary circuit to quench the arc or flow of electrons in the tube, or a suitable gas may be employed to quench the arc (as described previously under the construction of the G-M counter). A definite time is required to neutralize positive ions produced by one pulse and to ready the tube for the next ionization. The length of time required for this phenomenon is of the order of 100 to 200 microseconds. The time during which the tube is thus incapacitated is called the resolving time of the counter.

In a tube that has a resolving time of 200 microseconds, the tube should be able to accurately count 5,000 evenly spaced pulses per second. Since the disintegration of radioactive nuclei is not an evenly spaced phenomenon but is dependent upon probability, many counts are missed in a practical circuit because the time separation between counts may be more or less than 200 microseconds. As a result of this, regardless of the counting rate, some pulses must be missed, and these pulses are referred to as coincident pulses.

It is possible to set up a demonstration that clearly illustrates the behavior of the G-M counting circuit relative to the dead-time of the tube. The center conductor of the G-M tube is connected to the positive terminal of a power supply through a high resistance. After the tube registers a count, the voltage on the tube drops to a point where the tube is insensitive to ionization. After the arc in the tube has been extinguished, the voltage is in the proportional counting range. The initial ionization produced by a radioactive ray passing through the tube produces a pulse, but the pulse is of so low a magnitude that it cannot be recorded by the electronic recording apparatus. Such a pulse, however, can be readily observed by a sensitive oscilloscope attached directly to the center conductor of the G-M tube through a coupling capacitator.

As the elapsed time between consecutive impulses increases, the voltage on the G-M tube rises and the resulting pulse height increases. After a sufficiently long period of time elapses following an initial pulse, the tube recovers fully and produces the maximum pulse height. Figure 10-1 illustrates the pulse height that results at time intervals of 100, 150, 200, 250, and 300 microseconds after an initial pulse at zero microseconds. It must be understood that only a single following pulse is represented by this diagram. Should a second pulse occur 200 microseconds after the initial pulse, the voltage produced would be of the order of .85 volts. Should a second pulse occur 250 microseconds after the initial pulse, the voltage would be 1.06 volts. Should the pulse, however, occur within 120 microseconds, the resulting voltage would be less than 0.25 volts.

It is possible to adjust the electronic circuit built into the counter to respond to any preset threshold voltage. For practical purposes, threshold voltages of 0.25 volts are commonly used. This means that the counter records a count only if the peak pulse height is more than 0.25 volts. By connecting the height of the pulses in Fig. 10-1 with a solid line, it can be observed that the voltage does not reach the threshold value if the second pulse occurs within 120 microseconds. The tube and counter arrangement, therefore, is said to have a counter resolving time of 120 microseconds.

In order to observe this phenomenon on the oscilloscope, it is necessary to adjust the synchronizing control so that a pulse initiates the sweep circuit on the oscilloscope. It is also necessary to have the oscilloscope equipped with a calibrated sweep time base. In this type of an arrangement, a pulse initiates the sweep circuit and successive pulses appear on the oscilloscope. The time interval can be read from the time base. A representation as shown in Fig. 10-1 represents a total of five separate sweeps.

In order to determine the scaler sensitivity or the threshold voltage required to record a count, it is necessary to manually reduce the voltage to below the Geiger threshold and to a point where no counts are recorded on the counter. The oscilloscope continues to show the pulses produced by the ionization. The voltage is now gradually increased until the first counts are recorded by the scaler system. The voltage represented by the pulses can be determined by the voltage calibration system of the oscilloscope.

While the pictorial display of the resolving time, recovery time, and pulse height described here is very informative, it is not the most practical way to determine the resolving time of a G-M counter and scaler system. The practical and rapid method of making this determination is based on the fact that the counter is insensitive to counts for a period of time represented by t_r. If the tube actually counts n per second, the tube is insensitive for nt_r seconds. If a total of N events occurs each second, the number that the tube misses is equal to the rate per second times the portion of the second that the tube is insensitive, or Nnt_r. Now, the number of counts missed by the tube is also equal to N - n, the number of events per second minus the number of counts per second. Consequently, N - n is equal to Nnt_r. This equation can be reduced to

$$N = \frac{n}{1 - nt_r}$$

The above equation is essential in determining the total number of counts N when the number of observed counts n and the resolving time t_r are known.

If a total of three readings using two samples is made, first reading the samples individually and then reading the samples simultaneously, enough information is obtained to calculate the resolving time from the three related equations. Let n_1 be the number of observed counts for the first sample, let n_2 be the number of counts for the second sample, and n_{12} be the number of counts for the samples read simultaneously. The equation for the resolving time t_r is then given by

$$t_r = \frac{n_1 + n_2 - n_{12}}{2n_1n_2}$$

In order that the calculated resolving time yields the results in terms of seconds, the counts n must be in counts per second. Furthermore, the usual precaution must be taken to determine the background count and to subtract the background count from the recorded counting rate.

Once the counter resolving time is known, the number of events N can be calculated by the equation previously given

$$N = \frac{n}{1 - nt_r}$$

Since in practice it is necessary to solve this equation many times, nomograms for correcting counting rates of pulse counters have been developed. A very useful nomogram was published in The Review of Scientific Instruments, 21, 191, 1950.

QUESTIONS

1. What is meant by the resolving time of a counter?
2. Why is it necessary to make a correction for the resolving time of a counter?
3. What two effects make the G-M counter insensitive to incoming counts?
4. Describe the phenomenon of electron multiplication in a gas-filled counter.
5. Why is it convenient to operate the G-M tube above the Geiger region?
6. What is meant by coincident counts?
7. What effect does the preset threshold voltage have on the resolving time?
8. Why is it important to use the same type of planchet for an experiment to determine the resolving time of the counter?
9. What would be the effect of using a paper planchet for the second portion of the experiment and a lead planchet for the first portion of the experiment?
10. Approximately how many counts per second can successfully be measured with a G-M counter?

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11

calibration of a g-m counter end window

PLAN OF INSTRUCTION

OBJECTIVE

1. To study the end-window counter.

2. To determine the efficiency of the end-window G-M counter for beta rays.

3. To determine the effect of beta ray absorption in air and in the window of the G-M counter.

4. To develop an experimental method for correcting the errors introduced by absorption.

5. To develop a formula to give the total counting rate from the observed rate by making the corrections for absorption, resolving time of the counter, and the limited solid angle subtended by the counter window.

INTRODUCTION

1. Review the behavior of radioactive rays produced by the nuclide and the absorption and subsequent loss of energy of the beta particle.

2. Show that beta rays would travel in straight lines and would have an infinite range in a vacuum.

3. Review the effects of backscattering and absorption of beta rays.

TEACHING PLAN

1. Many experiments do not require a measurement of the absolute counting rate. Measurements of the half-life and other phenomena employed in tracer work can be performed by knowing only the relative ratio of counts.

2. Certain critical experiments require a knowledge of the absolute rate at which beta particles are produced. For instance, in the determination of radioactive doses to be taken internally, it is necessary to know the exact rate of decay.

3. The following factors must be known in order to determine the total rate of disintegration:

   a. The number of counts observed on the counting system
   b. The solid angle subtended by the counter window
   c. The correction factor due to the resolving time
   d. The correction for backscattering
   e. The correction for absorption of beta particles in the counter window
   f. The correction for absorption of beta particles in air between the source and counter window
   g. The correction for the absorption of beta particles in the covering foil (if one is used)
   h. The correction for the self-absorption and scattering in the source itself

4. This experiment is designed to supply the correction for the absorption due to the window, the air, and the covering foil.

5. Backscattering can be reduced to a minimum by depositing the radioactive material on a very thin backing.

6. Self-absorption can be held to a minimum by making extremely thin deposits on the backing.

7. Standards for checking a counting system are produced by depositing a known number of nuclides on a thin film by the electroplating processes.

8. The number of atoms deposited is a function of the positive charge carried by the metallic ion in solution, the electroplating current measured in amperes, and the time in seconds, and is given by

$$N = \frac{6.28 \times 10^{18}\ It}{e}$$

where N is the number of atoms deposited, I is the current in amperes, t is the time in seconds, and e is the number of charges carried by the metallic ion in units of electrons.

9. The number of disintegration per second is now given as $N\lambda$ where λ is the disintegration constant.

10. The total number of radioactive nuclides on a standard can also be calculated by diluting a known mass of a radioactive substance in a known quantity of solvent. A series of dilutions are usually employed until the number per ml is in the region desired. A known volume of the solution is then placed on a thin film and evaporated. Using this technique, the number of radioactive nuclides on a standard is equal to

$$N = \frac{\text{mass of sample in grams}}{\text{atomic weight of nuclide}} \times 6.0427 \times 10^{23}$$

If the nuclide is part of a molecule, it is necessary to use the molecular weight of the compound containing the nuclide.

APPARATUS

End-window G-M tube with rack to hold tube and vial

G-M scaler with variable voltage control

Timing system, such as a timer or clock

Carbon-14 as sodium carbonate (Available from Nuclear-Chicago, Inc., No. RCB-1)

Set of aluminum foils approximately 10 mils thick for absorbers

EXPERIMENTAL PROCEDURE

1. Prepare a sample of carbon-14 by depositing 0.5 ml of carbon-14 (sodium carbonate) on a filter paper.

2. Evaporate the water in the solution under a sun-lamp.

3. Mount the filter paper on a planchet holder by means of scotch tape. Do not use a metallic planchet, because it will increase the backscattering.

4. While the carbon-14 sample is drying, make a determination of the resolving time of the counting system as described in Session 10.

5. Refer to the manufacturer's specifications for the thickness of the end window of the G-M tube. This is usually given on the label attached to the tube.

6. Measure the distance of the air column separating the window of the G-M tube and the radioactive source.

7. Calculate the mg/cm^2 of air between the source and detector by multiplying the separation in centimeters by 1.23 mg/cm^3.

8. Measure the area of a number of plates and determine the mass in grams by weighing the plates.

9. Determine the mg/cm^2 of the aluminum absorbers.

10. Determine the background count correction by taking a minimum of five one-minute determinations.

11. Place the paper containing the carbon-14 sample in the sample holder and make a series of five readings of the counting rate.

12. Add one absorber and measure the activity.

13. Continue adding absorbers until the counting rate is down to approximately 5 percent of the original rate.

14. Plot the activity and counts per minute on a log scale as the ordinate against the total mg/cm^2 as the abscissa.

15. The initial reading should be plotted on an abscissa that takes into account the thickness of the end window and the absorption due to air. Subsequent readings should include the total amount of absorbers in the system, the end window, the column of air, and the aluminum absorbers.

16. The series of points on semi-log paper should result in a straight line that gives the value of the count with zero absorption when extrapolated to zero thickness on the abscissa.

17. Determine the number of counts corrected for resolving time by

$$N = \frac{N_o}{1 - N_o t_T}$$

18. Determine the solid angle subtended by the counter by dividing the area of the counter window by the separation between the counter window and the radioactive source. (This is strictly true only if the area of the window is small compared to the separation.)

19. The total number of disintegrations can now be obtained by

$$D = N \frac{4\pi}{\Omega}$$

where D is the disintegration rate of the sample, N is the corrected extrapolated value of the count rate, and Ω is the solid angle subtended by the counter.

RESOURCE MATERIAL

When it is necessary to determine accurately the total number of disintegrations of a sample, additional precautions must be taken to assure that the results actually represent the number of disintegrations produced in the source. It is convenient to think of a point source of radioactivity and of a source that is so small that there is no self-absorption in the sample. Under these circumstances, the radiation is uniform in all directions from the source. If no cover plate is used to cover the sample; if the sample is in a vacuum, the rays produced will continue indefinitely.

In a practical case, however, the radioactivity is rarely confined to a point source so that some self-absorption does not occur in some direction. For instance, most of the available sources are deposited on a thin backing, and the thin layer of radioactivity is distributed over an area of approximately one square inch. Rays emerging perpendicular from the sample are not affected by self-absorption, but rays that initially start out parallel to the sample suffer self-absorption or absorption in the backing material. This experiment is limited to rays emerging at right angles to the sample.

To the first approximation, the number of rays that activate a G-M counter are that portion of the total which impinge on the surface of the G-M tube. When the voltage of the G-M tube is adjusted to the counting plateau, the intensity of the electron-avalanche is independent of the initial ionization produced, and a single electron dislodged by the passage of a beta particle will produce a count. Therefore, if the beta ray enters the end-window of a counting tube, it can be assumed to initiate a count. The total number of counts produced by a G-M tube, therefore, are proportional to the solid angle subtended by the end-window of the tube. This equation may be written as

$$n_a = \frac{kD\Omega}{4\pi}$$

where n_a is the apparent count, k is the constant depending upon other factors, D is the disintegration rate, and Ω is the solid angle subtended by the end window of the tube.

The solid angle can be approximated by dividing the area of the end window by the distance between the source and the window. Where the distance between the source and window is equal to the diameter of the window, an error of 10 percent may be made when using this approximation. To be more correct, the separation should be of the order of two to three times the diameter of the end window.

The correction for backscattering can be made negligible by depositing the nuclide on a very thin backing. This can be accomplished by making the deposit on a filter paper. Self-backscattering, likewise, can be avoided by making the deposit of the nuclide as thin as consistent with adequate counts. When a very thin sample is used, self-absorption is likewise reduced to a negligible factor. A covering foil produces an error; this can be avoided by the elimination of the covered foil. A very thin spray film of a collodion, such as hair spray, may be used to prevent loss of dry material. Special samples should be prepared immediately prior to performing the experiment.

The following two types of absorption cannot be eliminated without special equipment:

1. Absorption in the column of air between the sample and window
2. Absorption in the window itself

Special G-M tubes are made to eliminate the absorption of the column of air and the absorption in the window and are suitable for certain types of counting. For instance, carbon-14 in the form of methane gas may be introduced directly into the G-M counter, eliminating both the window and the absorption in air. Counters of this kind accurately count the total number of disintegrations due to carbon-14.

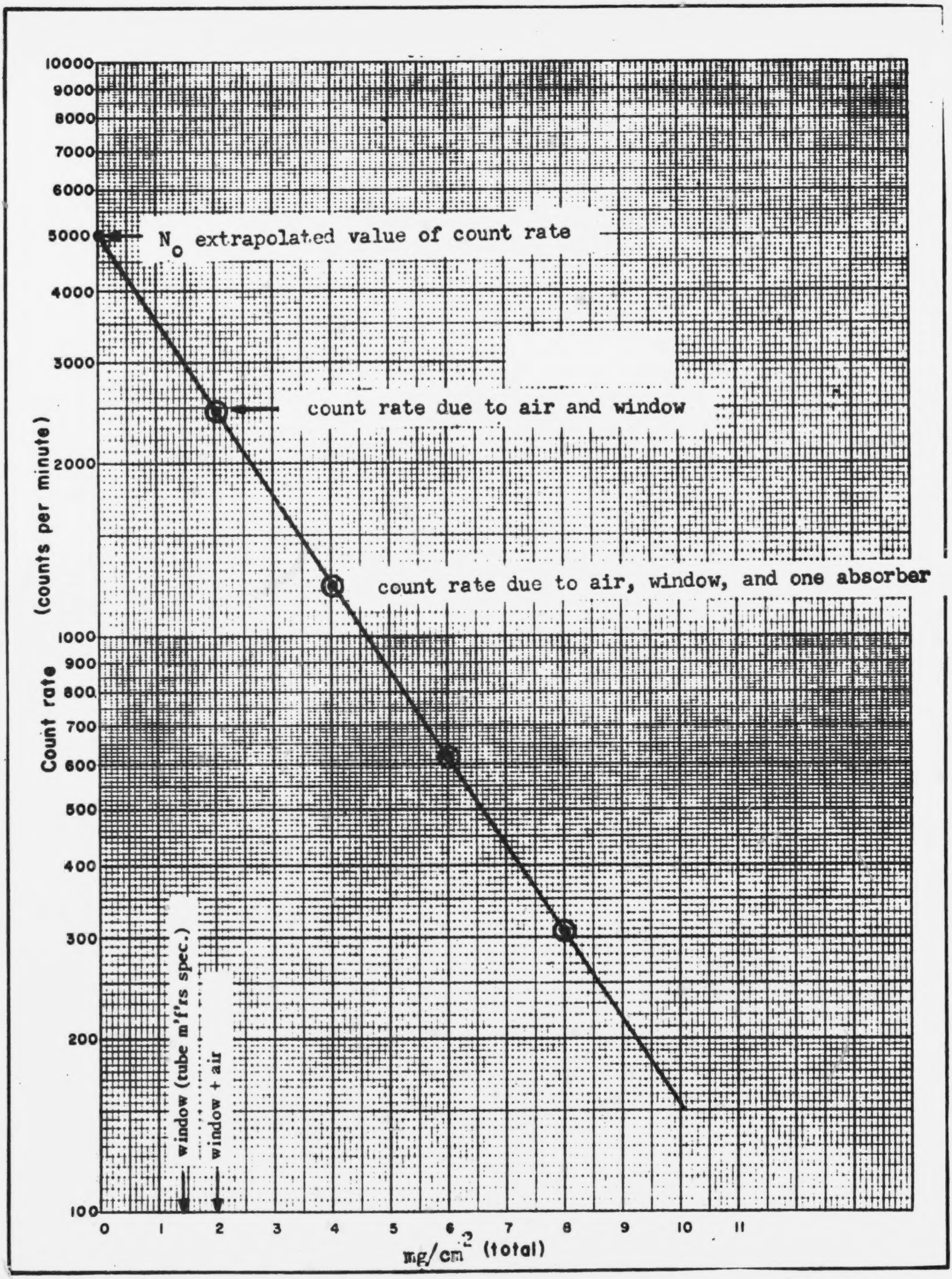

Fig. 11-1. Experimental determination of window and air absorption factors using a carbon-14 source.

The correction for the absorption by air is made by calculating the mass of air in mg/cm^2 between the sample and the window. This is numerically equal to 1.23 mg/cm^3 times the separation between the source and detector in centimeters.

The end-window tube suitable for carbon-14 counting must have a window thickness from 1.4 to 2.0 mg/cm^2. Other windows, used primarily for high-energy beta particles such as those from phosphorus-32, have a window thickness from 3 to 4 mg/cm^2. Glass tubes with a wall thickness of 30 mg/cm^2 are unsuitable for counting carbon-14. The exact window thickness is available from the manufacturer's specifications for the tube and is in a quantity that cannot be measured without destroying the tube.

By means of an experiment involving the counting rate produced when additional absorbers are used, it is possible to extrapolate the curve to a zero reading. Figure 11-1 illustrates a curve drawn on semi-log paper from points plotted for the initial count rate due to the air and window and successive count rates due to air, window, and one or more absorbers. The abscissa is in units of mg/cm^2, and the ordinate is in terms of the observed count. A straight line passing through the observed points will intersect the zero absorber thickness, and the number on the ordinate is the extrapolated value of the count rate.

Finally, it is necessary to apply the correction for the resolving time of the counter and associated electronic equipment. It is necessary, therefore, to repeat the resolving time for the particular combination of G-M tube and counting equipment being used and to apply the formula derived in Session 10.

The disintegration rate can then be calculated from the formula

$$D = N \frac{4\pi}{\Omega}$$

QUESTIONS

1. In what kind of practical problems is it necessary to know the actual number of disintegrations in the sample?
2. Why is it necessary to calibrate the G-M tube?
3. How is self-absorption and backscattering minimized in this experiment?
4. Calculate the mass of air in mg/cm^2 for a separation of 3 cm between the window and the sample.
5. If the glass tube has a wall thickness of 30 mg/cm^2, is the method described in this experiment valid for the calibration?
6. The chart used for the purpose of extrapolating the count rate to zero thickness, Fig. 11-1, is a semi-log chart. Suggest the reason for using semi-log charts in this experiment.
7. Why is it necessary to redetermine the resolving time of the G-M counter?
8. What uncorrected errors are still present in this experiment?

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12 statistical variation in radioactive measurement

PLAN OF INSTRUCTION

OBJECTIVE

1. To study the statistical variations in counts produced by a radioactive sample.
2. To understand the term probability as it relates to the radioactive decay of a substance.
3. To tabulate a series of counts and calculate the probable deviation from the average number of counts.
4. To understand the reason for a large number of separate counts as compared to a single measurement with a large number of counts.
5. To become acquainted with the formulas that predict the reliability or precision of the counts recorded by the G-M counter.

INTRODUCTION

1. Review the random characteristic of radioactive decay.
2. Compare the random distribution of radioactive decays to such other random phenomena as flipping a coin and throwing dice.
3. Review the formulas predicting the number of radioactive decay, the total number of atoms, and the time constant.
4. Review the further complicating characteristics of the G-M counter wherein the counter is insensitive during the time that is required for the ion field to clear in the counter.

TEACHING PLAN

1. Radioactive disintegration is a random function in time.
2. The probability that a particular atom undergoes a disintegration is a function of probability and is inversely proportional to the half-life of the atom.
3. The rates at which counts are observed on a G-M counter is based upon probability and two successive readings of the counter will not necessarily yield the same result.
4. The random processes in disintegration obey the laws of statistics, which predict that the number actually counted in a given time will show deviation from the average, even though there is a definite rate of disintegration.
5. If proper care is taken to keep all experimental conditions constant, the true value of a count can be obtained as an arithmetic mean of a very large number of observations.
6. If a series of counts are made on a radioactive sample, the fluctuation of individual observed counts about the arithmetic mean will have a normal, or Poisson, distribution.

The standard deviation σ is expressed in formula form as

$$\sigma = \sqrt{N}$$

where N is the number of counts.

7. It can be shown that about 67 percent of the measurements deviate less than an amount σ from the mean.

8. The probable error P.E. is the error that has equal probability of being exceeded or not exceeded and is given by

$$P.E. = 0.67\sqrt{N}$$

9. About 50 percent of the measurements deviate by less than the probable error, or less than 0.67 times $\sqrt{N}$.

10. The relative deviation σ_r is the standard deviation expressed as fractions of N, or

$$\sigma_r = \frac{\sigma}{N} = \frac{1}{\sqrt{N}}$$

11. The background count, likewise, is subject to the same laws of statistics, and the standard deviation of the background count is obtained by

$$\sigma_b = \sqrt{N_b}$$

where N_b is the background count.

12. The net standard deviation then becomes equal to the square root of the sum of squares of the standard deviation due to background and the standard deviation due to observation of counts:

$$\sigma_t = \sqrt{\sigma_b^2 + \sigma_s^2}$$

where σ_t is the combined standard deviation, σ_b is the background standard deviation, and σ_s is the standard deviation for the sample. More simply stated,

$$\sigma_t = \sqrt{N_b + N_s}$$

where N_b is the background count and N_s is the total count (background plus radiation).

APPARATUS

G-M tube with rack to hold tube and sample

G-M scaler with variable voltage control

Timing system, such as a timer or clock

Any beta active sample arranged to give approximately 1,000 counts per minute

EXPERIMENTAL PROCEDURE

1. Arrange the counting equipment to record approximately 1,000 counts per minute.
2. Make twenty successive counts of one minute each with the radioactive sample, taking care not to change the geometry of the apparatus.

3. Find the arithmetic mean of the counts by adding the counts together and dividing by the number of observations made.

4. Plot the number of observations that fall between the arithmetic mean and the arithmetic mean plus ten.

5. For each range of ten in successive counting rates, plot the number of occurrences both above and below the arithmetic mean (If an infinite number of observations were made, the resulting curve would be the Poisson distribution curve).

6. Make a similar series of observations to determine the background and plot the background distribution.

7. Determine the standard deviation for the sample, correcting the counts for background counts.

8. Determine the standard deviation for the background count.

9. Determine the standard deviation for the combination of sample and background by

$$\sigma = \sqrt{N_s + N_b}$$

10. Calculate the relative deviation

$$\sigma_r = \frac{\sqrt{N_s + N_b}}{N_s - N_b}$$

11. Finally, calculate the relative probable error by multiplying the relative deviation σ_r by 0.67.

12. Multiply the relative probable error by 100 to arrive at the relative probable error expressed in percent. In order to obtain reliable data on radioactive samples, the relative probable error should be 5 percent or less.

13. With the background count, determine the number of counts with the sample in place (N_s) in order that the relative probable error is less than 5 percent and, finally, less than 1 percent.

RESOURCE MATERIAL

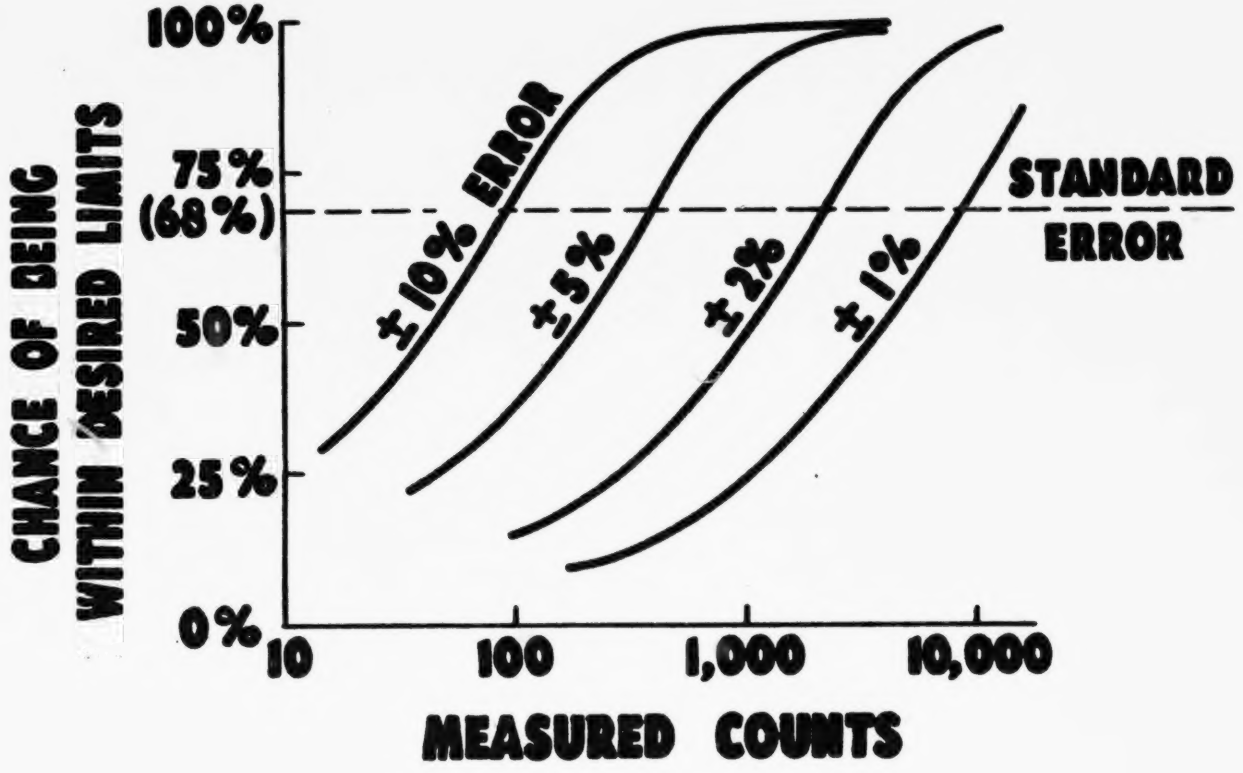
When random radiation measurements are made, the fluctuations are found to follow the laws of probability and the equations worked out for random phenomena are found to hold. Other instances of random variations occur in such a simple phenomenon as tossing a penny, where the probability of finding either heads or tails should be exactly one to one. If a penny is tossed a given number of times, however, the ratio may differ from one to one, especially if the number of tosses of the penny is limited. In an infinite number of tosses, the ratio will be found to be exactly one to one.

When radioactive samples are counted, it will be noted that the counts are never exactly the same, but they cluster around a value that is known as the arithmetic mean. The mean is determined by averaging all of the observed counts.

The student will make a series of twenty successive counts with the same radioactive sample without changing the geometry of the sample. With a counting rate of between 1,000 and 2,000, the deviation from the mean will be seen to increase with the counting rate but will not be proportional to the counting rate. That is, the deviation from 2,000 counts per minute for successive counts will not be equal to twice the deviation noted for 1,000 counts per minute but something closer to 40 percent more. The standard deviation of a single observation of N counts is defined as $\sqrt{N}$. Thus, the standard deviation for 1,000 counts is 31.3 and for

NEED FOR LARGE COUNTS

TO REDUCE ERROR



HIGH PROBABILITY OF LOW ERROR REQUIRES HIGH COUNT

2,000 counts 44.7. The probable error is that error which is equal to the probability of being exceeded or not being exceeded and is 0.67 times the standard deviation. Similarly, for 1,000 and 2,000 counts the probable error is 21 and 30. Stated in another way, about 50 percent of the deviations are less than 0.67 σ and 5 percent of the deviations are greater than twice the square root of the mean, or 2 σ.

It is often desirable to express the deviation in terms of a decimal or percent. Thus a new unit called the relative deviation σ_r is defined as the standard deviation divided by σ/N, or $1/\sqrt{N}$. The relative probable error for the 1,000 and 2,000 count is, therefore, 0.32 and 0.22 or expressed in terms of percent, 3.2 percent and 2.2 percent. In order to reduce the relative probable error to 1 percent, it is necessary to increase the number of counts to 10,000.

In a practical counting situation, a series of two counting operations are made, one a sample of the total count N_s and the other a sample of the background N_b. The standard deviation for the combination is obtained by the formula

$$\sigma_t = \sqrt{\sigma_b^2 + \sigma_s^2}$$

The relative probable error for this case is equal to the net standard deviation divided by the net counts. The net count is obtained by using $N_s - N_b$. Consequently, the relative probable error is

$$\sigma_r = \frac{\sqrt{N_s + N_b}}{N_s - N_b}$$

It is left to the student to determine that in order to achieve 5 percent accuracy in the case where the background count can be neglected, it is necessary to make a total of 400 counts. However, if the background count is approximately equal to the count for the sample (i.e., $N_s = 2N_b$), N_s must equal 2,400 and N_b equals 1,200.

Similarly, in order to reduce the relative probable error to 1 percent, N_b count would be 30,000 and N_s would be 60,000.

It is evident from this that if there is an appreciable background count, the counting time required materially increases. Conversely, the relative probable error increases very rapidly as the background count increases. For this reason, the greatest care must be exercised in designing the counting geometry so that background count is reduced to the lowest possible value.

Background count is due to cosmic radiation and due to contamination. If the background counting rate is greater than 40 counts per minute, the counting equipment should be carefully checked for possible sources of contamination.

QUESTIONS

1. Why don't successive one-minute counting periods yield the identical results for a radioactive sample?
2. A rate meter is designed to indicate the number of counts per minute on a D'Arsonval-type galvanometer. Would you expect this meter to give a steady reading?
3. What is meant by the random processes in disintegration?
4. What precaution must be made in order to obtain the true reading for a sample?
5. If the arithmetic mean value is 1600, what is the expected fluctuation of an individual observed count about this mean value?
6. Out of 20 counts made on a sample, how many can be expected to deviate more than the amount σ from the mean where

$$\sigma = \sqrt{N}$$

7. What additional precautions must be made if the background count is more than 10 percent of the counting rate of the sample?
8. Why must the geometry of the experimental procedure remain the same during the 20 successive counts on the sample?
9. Describe two other phenomena common to gambling that are based on probability and are consequently governed by the laws of statistics.
10. Is it possible to "talk to the dice" and consequently change the laws of probability?
11. Show that if the background count can be neglected, it is necessary to make a count of a total of 400 in order to achieve an accuracy of 5 percent in a single measurement.
12. Show that if the background count N_b equals 1,200, the sample count N_s must equal 2,400 in order to achieve a 5 percent accuracy.
13. What precautions can be made to decrease the background count in your experimental setup?
14. List four sources of counts that are responsible for the major background counting rate.

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13

determination of range and energy of alpha particles

PLAN OF INSTRUCTION

OBJECTIVE

1. To determine the range of alpha particles in air.
2. To verify the equations for energy as a function of range for alpha particles in air.
3. To determine the air equivalent of absorbers for alpha particles.
4. To calculate the depth of penetration of alpha particles in animal tissue.
5. To determine the necessary shielding for complete protection from radiation produced by alpha particles.

INTRODUCTION

1. Review the radioactive decay products for elements with atomic mass 82 and above.
2. Review the structure of heavy elements and the mechanics of emission of alpha particles that result in the production of daughter elements.
3. Review a simple nuclear reaction involving the masses of parent, daughter, alpha particle, and excess mass.
4. Review Einstein's mass to energy equation $E = mc^2$ by which it is possible to calculate the energy of the alpha particle.

TEACHING PLAN

1. An alpha particle is the fast-moving nucleus of the helium atom.
2. Alpha particles are generally produced by radioactive elements with atomic numbers larger than 82; however, a few alpha emitters are found among other radioactive elements.
3. Since the alpha particle carries two positive charges and since neutral atoms are surrounded by orbits of negatively charged electrons, attractive interaction forces exist between the particles.
4. Three simple phenomena are observed:
   a. The electron is attracted to the alpha particle but is not completely removed from the nucleus. This results in raising the electrons to a higher energy level and the excited atom emits a photon of visible or invisible energy.
   b. The attraction forces are great enough to remove an electron entirely from the interacting atom, resulting in the formation of a free electron and a positively charged ion, referred to as an ion pair.
   c. The alpha particle, if it penetrates deep into electron shells, is repelled by the positively charged nucleus, causing the alpha particle to be deflected or scattered.

5. Only a small fraction of the energy of an alpha particle is lost in a single interaction with a neutral atom.

6. The number of interactions per centimeter of travel depends upon the length of time that the alpha particle is in the vicinity of a neutral atom. Thus, low-energy alpha particles lose more energy and produce more ion pairs in a centimeter of travel than high-energy alpha particles.

7. Contrary to the behavior of gamma rays where the absorption is a "one-shot" phenomenon, the gradual loss of energy per centimeter length results in a finite range for alpha particles.

8. The range of alpha particles is the function of energy and is approximately proportional to the 3/2 power of the energy.

9. The velocity of the alpha particle is proportional to the cube root of the range.

10. Absorbers of different atomic number have different effects on alpha particles. In general, as the atomic number increases, the relative stopping power of the absorber increases.

11. A convenient determination of the range is made by the use of absorbers and the concept of the air equivalent of absorbers.

APPARATUS

A Landsverk electroscope

A point alpha source

A source holder and lead shield

EXPERIMENTAL PROCEDURE

1. Arrange the apparatus as indicated in Fig. 13-1.

2. Put the radioactive alpha source about 0.3 cm down the lead cylindrical source holder; this will produce a collimated beam of alpha particles and will shield the operator from radioactive rays.

3. Charge the electroscope with the battery provided and observe the rate at which the fiber drifts across the screen. The drift rate in divisions per minute must be subtracted from the observed drift rate with the sample in place.

4. Raise the alpha source as high as possible and take a reading on the drift rate in terms of divisions per minute.

5. Lower the elevator plate (using the wing nut) at intervals of 0.5 cm for a total distance of 6 cm.

6. Record each drift rate, subtracting the no-signal drift rate, and plot the drift rate of the electroscope in divisions per second against the range in centimeters from the source to the screen. In this measurement include the 0.3 cm the alpha source was recessed in the collimating source holder.

7. From the straight portion of the curve, extrapolate to the range axis to obtain the range in centimeters.

8. Place a suitable absorber on top of the source holder to absorb some of the alpha rays being emitted and repeat the series of readings. An aluminum absorber 3.2 mg/cm^2 thick should produce the same absorption as 2 cm of air. Consequently, the range should be decreased by that amount. A gold absorber 4 mg/cm^2 thick should reduce the range by approximately 1 cm.

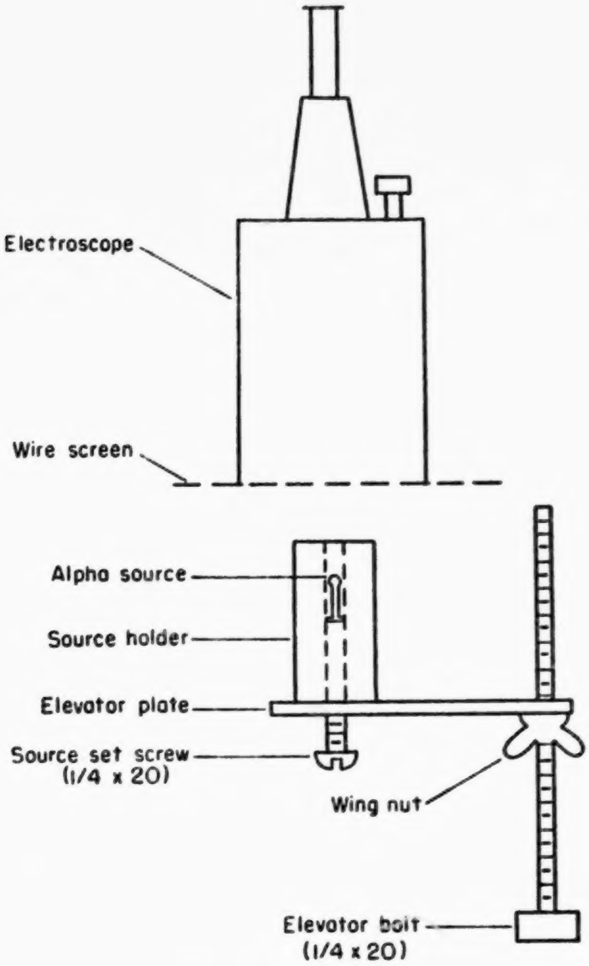
Electroscope
Wire screen
Alpha source
Source holder
Elevator plate
Source set screw (1/4 x 20)
Wing nut
Elevator bolt (1/4 x 20)

Fig. 13-1. Arrangement of apparatus to determine range and energy of alpha particles

9. From the formula

$$R = 3.1\ E^{1.5}$$

calculate the range for the alpha particle used in the experiment. The energy is given in Table 2-2.

10. From $R_{air}\ \rho_{air} = R_{tissue}\ \rho_{tissue}$, where $\rho_{air} = 0.0013$ grams/cm^3, $\rho_{tissue} = 1$ gram/cm^3, and $R_{air} = 5$ cm, calculate the range of alpha particles in human tissue.

RESOURCE MATERIAL

Alpha particles are the nuclei of helium atoms. They are emitted from radioactive elements generally found among those with atomic mass larger than 82, although a few alpha emitters are scattered through the remaining elements.

Alpha particles are emitted with considerable velocity from the nucleus of the atom, and the spread of energy of the alpha particle is from nearly 0 Mev to 10 Mev. The energy with which the alpha particle is emitted from the nucleus of the atom can be calculated by the method illustrated in Session 2 by subtracting the mass of the daughter element and the mass of the alpha particle from the parent mass. The remaining mass in amu multiplied by 931 yields the energy in Mev that the alpha particle has when it emerges from the parent nucleus.

The question of why an alpha particle is emitted rather than a neutron, a proton, or one of the other light nuclides can be seen by calculating the kinetic energy release by substituting these nuclides in the formula referred to above. It will be noted that for all of the other nuclides, kinetic energy must be added to the reaction and only for the helium nuclei is there a positive energy. Table 13-1 lists the energy released for all possible modes of decay for uranium-232. Negative energy release means that energy must be added to the reaction. As can be seen from the chart, ${}_2He^4$ emitted from uranium-232 has an energy of +5.38 Mev.

Table 13-1
KINETIC ENERGY RELEASE FOR VARIOUS MODES OF DECAY OF U^{232}
(Computed from known masses)

Emitted Particle	Kinetic-Energy Release Mev	Emitted Particle	Kinetic-Energy Release Mev
n	-7.15	He^4	+5.38
H^1	-6.05	He^5	-2.28
H^2	-10.5	He^6	-5.82
H^3	-10.1	Li^6	-3.78
He^3	-9.6	Li^7	-1.83

(From Introductory Nuclear Physics by David Halliday. 2d ed. Copyright 1955. John Wiley & Sons, Inc, New York. Used by permission.)

The alpha particle has a mass of 4 and a charge of +2. As compared to the velocity of a beta particle, an alpha particle is moving with a comparatively low velocity. Interaction between the positive charge of the alpha particle and the electrons surrounding the nucleus of the atom result in the formation of ion pairs by the following process. As the alpha particles approach the electrons, the attraction forces between electrons in the outer shell and the positive nucleus cause an electron to be freed from the forces of the stable atom. The absence of one electron leaves the atom with one positive charge. Energy is expended in this process, and in dry air an average energy of 35.5 ev is required to produce an ion pair. The energy required to produce an ion pair varies from 26.4 for argon to 42.7 for helium, depending on the type of gas employed.

For alpha particles with an energy of 5 Mev, 3×10^4 ion pairs per centimeter are produced in dry air at atmospheric pressure. With an energy of 35.5 ev per ion pair, approximately 1 Mev/cm is expended in the alpha particle.

The energy expended per centimeter is not a constant and varies from 1.4 Mev/cm for .1 Mev alpha particles to 2.5 Mev/cm for 0.7 Mev alpha particles. Energy drops to 0.1 Mev/cm for 100 Mev alpha particles and to 0.01 Mev/cm for 3,000 Mev alpha particles. This phenomenon is explained by the fact that a fast-moving alpha particle spends less time in the vicinity of the atom and, therefore, reacts less with the electrons surrounding the atom.

For alpha particles produced by naturally radioactive elements, the range of energy is from 0 to approximately 10. In this region the loss per centimeter is relatively constant but increases for energies less than 0.5 Mev. This is known as the Bragg hump.

Since the alpha particle emitted has a specific energy and since it loses a small fraction of this energy with each interaction, the gradual loss of energy is responsible for the finite range of the particle. Unlike gamma rays, where the interaction is a "one-shot" phenomenon, the range of the alpha particle is definite. In the region between 4 to 7 Mev, the range in dry air at atmospheric pressure can be given by the formula

$$R = 3.1\ E^{1.5}$$

If the range is known, energy can be given by

$$E = 2.1\ R^{0.67}$$

The velocity of the alpha particle can be calculated from the energy and the range equation and is given by

$$v^3 = Ra$$

where v is velocity in centimeters per second, a is 1.03×10^{27}, and R is the range. Figure 13-2 gives the relationship between the mean range in air and the energy of the alpha particle in Mev.

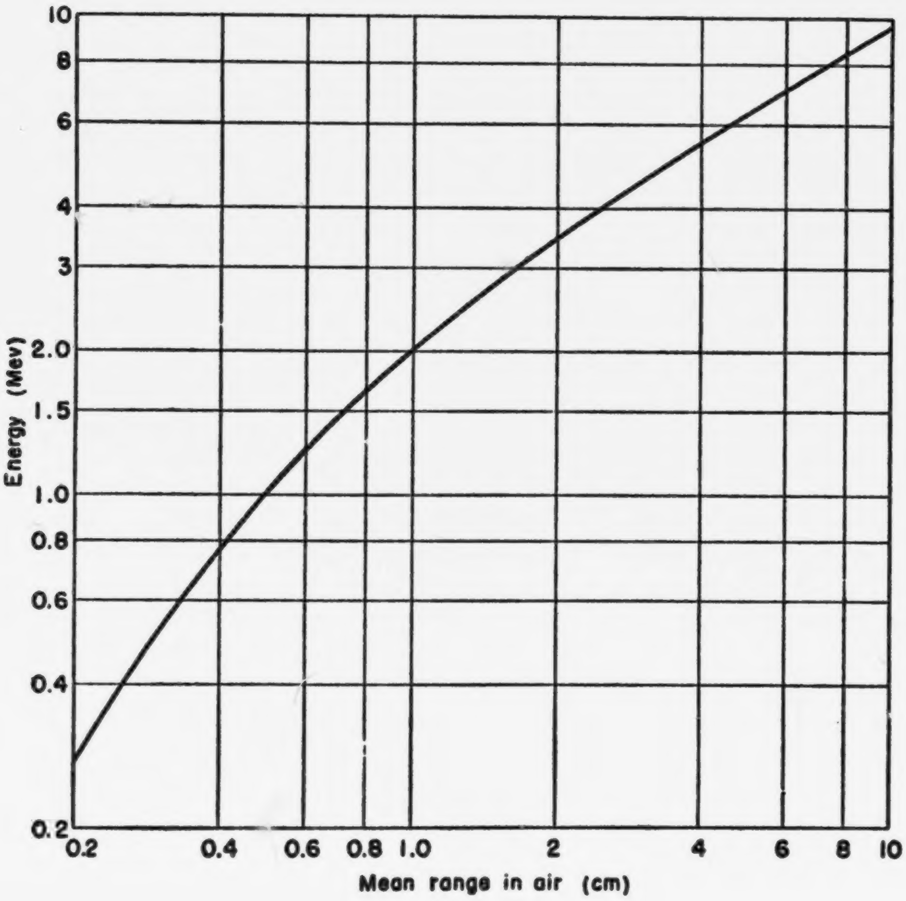

Fig. 13-2. Mean range in air as a function of energy for alpha particles (From Nuclear Radiation Physics by R. E. Lapp and H. L. Andrews. 3d ed. Copyright 1963. Prentice-Hall, Inc., Englewood Cliffs, N. J. Used by permission.)

It is often very useful to use absorbing foil in dealing with alpha particles. The use of an absorbing foil makes it possible to measure the range and energy of particles without changing the geometry of the source and detecting device, thereby eliminating the correction for the inverse square law.

Comparison of the range of alpha particles in air for solids may be made by using the concept of stopping power. Stopping power is the rate at which the alpha particles lose energy per increment of path in the absorber. A concept that is more easily visualized is that of relative stopping power, which is simply the ratio of the stopping power in air to the stopping power in solids. Table 13-2 compares the relative stopping power of a number of typical common absorbers for 7 Mev alpha particles.

Table 13-2
STOPPING POWER OF COMMON ABSORBERS

Absorber:	Mica	Aluminum	Copper	Silver	Gold
Relative stopping power:	2000	1660	4000	3700	4800
mg/cm^2 = 1 cm air:	1.4	1.62	2.26	2.86	3.96
Thickness (microns):	5.0	6.0	2.5	2.7	2.1

(From Nuclear Radiation Physics by R. E. Lapp and H. L. Andrews. 3d ed. Copyright 1963. Prentice-Hall, Inc., Englewood Cliffs, N. J. Used by permission.)

The table lists the thickness in microns required to produce the same stopping effect as 1 cm of air. An aluminum absorber with a thickness of 6 microns, therefore, would have the same effect on a 7 Mev alpha particle as a gold absorber with a thickness of 2.1 microns.

Table 13-2 also gives the equivalent thicknesses in mg/cm^2 for 1 cm of air. For practical purposes the absorber used in this experiment may be aluminum foil, such as that commonly found in the kitchen, and gold foil, obtainable from sign writers.

A third interesting phenomenon is the concept of the stopping power of an individual atom. The relative atomic stopping power s is defined as the number of atoms of air that are equivalent to one atom of the element used as the absorber. The atomic stopping power is 1 for air and increases as a function of the atomic number larger than air and also as a function of the energy. For alpha particles with an energy of approximately 2 Mev, a gold atom is as effective as three atoms of air. For alpha particle energies of 24 Mev, gold is, however, as effective as 5.3 atoms of air. The aluminum atom has nearly a uniform characteristic and is as effective as 1.5 atoms of air and is independent of energy. For this reason, aluminum is a suitable element to use for an absorber for alpha particles. Figure 13-3 gives the atomic stopping power of various elements for alpha particles with a range of energy.

The atomic stopping power for tissue found in animal matter is nearly equal to one. Consequently, the range is inversely proportional to the number of atoms per cubic centimeter or stated in another way as

$$R_{air} \rho_{air} = R_{tissue} \rho_{tissue}$$

Since it is possible to determine the range of alpha particles in air in this experiment or to find it in appropriate tables, it is possible to determine the range of alpha particles in human tissue. For alpha particles normally found in radioactive substances, the range is of the order of 50 microns (1 micron = 10^{-6} meters).

While the energies available from radioactive elements fall in a range between approximately 0 and 10 Mev, it is now possible to produce alpha particle energies up to and above 100 Mev by means of the cyclotron and other atomic accelerators.

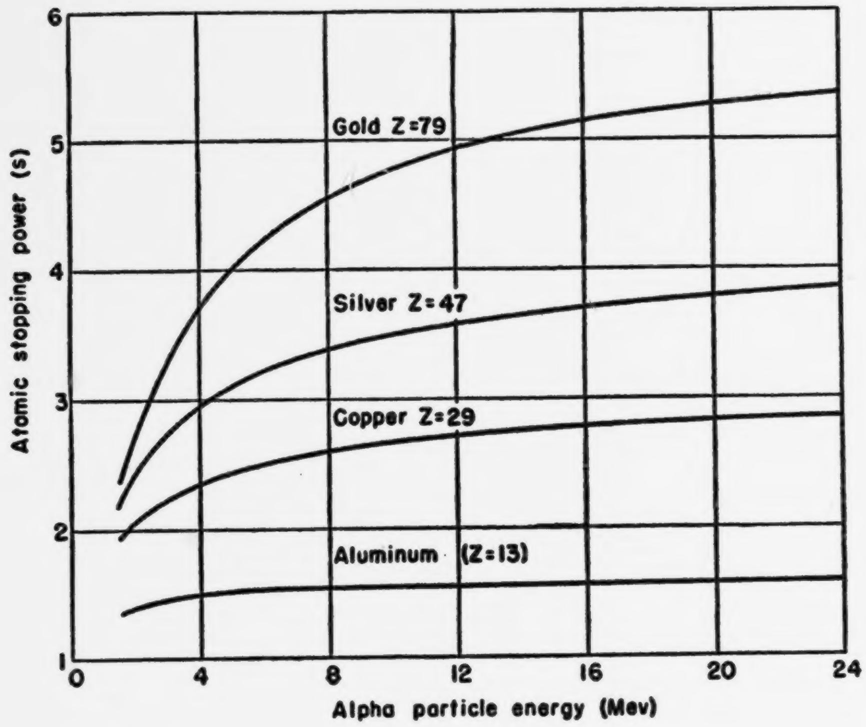

Fig. 13-3. Stopping power of various elements for alpha particles with a range of energy (From Nuclear Radiation Physics by R. E. Lapp and H. L. Andrews. 3d ed. Copyright 1963. Prentice-Hall, Inc., Englewood Cliffs, N. J. Used by permission.)

QUESTIONS

1. What is the relative mass of the alpha particle as compared to the beta particle?
2. Give the mass and charge of the alpha particle.
3. How much energy is required to produce an ion pair in dry air?
4. What is the approximate expenditure in energy when an alpha particle moves through 1 cm of air?
5. Give the simple explanation for increased ionization as the alpha particle slows up (Bragg hump).
6. Why is the absorption of energy from an alpha particle not a "one-shot" phenomenon?
7. Calculate the range of an alpha particle when the energy is 4 Mev.
8. What is the velocity of an alpha particle when the range is 4 cm? Compare your results with the range given in Fig. 13-2.
9. Calculate the thickness of a mica absorber for 7 Mev alpha particles that would have the same absorbing properties as a gold absorber with a thickness of 1 micron.
10. Estimate the atomic stopping power for 12 Mev alpha particles for (a) boron absorber and (b) iron.

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14

effect of magnetic fields upon beta and gamma rays

PLAN OF INSTRUCTION

OBJECTIVE

1. To study the effect of a magnetic field upon beta particles and gamma rays.
2. To determine the charge on the beta particle.
3. To determine the charge on the positron.
4. To study a method of separating various energy beta particles.
5. To produce a beam of particles by means of a slit.
6. To separate gamma rays from beta particles so that it is possible to count each independently without the use of absorbers.

INTRODUCTION

1. Review the left-hand rule for flow of electrons in a wire in a magnetic field.
2. Establish the direction of force on a moving electric current by assuming that the electrons flow from the negative terminal to the positive terminal.
3. Review the production of beams of electrons in a vacuum.
4. Review the similarity between flow of electrons in a vacuum and flow of electrons in a wire.

TEACHING PLAN

1. Beta particles are moving electrons traveling with velocities very near the velocity of light.
2. Positrons are positive electrons with characteristics similar to electrons except that the charge on the particle is positive.
3. Gamma rays are similar to X rays and to visible light and have no charge.
4. The energy of the gamma ray is a function of the wave length of the gamma ray.
5. Beta particles are deflected in the same manner by a magnetic field as an electron stream is confined to a wire.
6. The direction of the force on the electron is perpendicular to the velocity and perpendicular to the direction of the magnetic field; the direction of the magnetic field is defined as being from the north pole to the south pole.

7. The direction is determined by the vector equation

$$\frac{e(\bar{v} \times \bar{H})}{c}$$

8. The direction of the deflection of the positron is in the opposite direction to that of the beta particle but is likewise perpendicular to v and perpendicular to H.

9. In a uniform magnetic field, beta particles and positrons execute a perfect circle (in the absence of absorbing matter).

10. In a uniform magnetic field and with a homogenous source of beta particles, particles emerging from a slit will come to focus on a slit after completing a semicircle.

11. The radius of a curvature in a magnetic field is a complex function of the energy of the beta particle and is inversely proportional to the magnetic field.

12. Gamma rays are not affected by a magnetic field or an electric field because they have the properties of photons and, therefore, carry no charges.

APPARATUS

G-M tube with rack to hold tube and sample

G-M scaler with variable voltage control

Timing system, such as a timer or clock

A surplus Alnico V magnatron magnet

Lead foil sheet 1/32 inches thick

Phosphorus-32

Thallium-204

Sodium-22

Iodine-131 (All in soluble form.)

Four wide-mouth bottles or 100 ml beakers

EXPERIMENTAL PROCEDURE

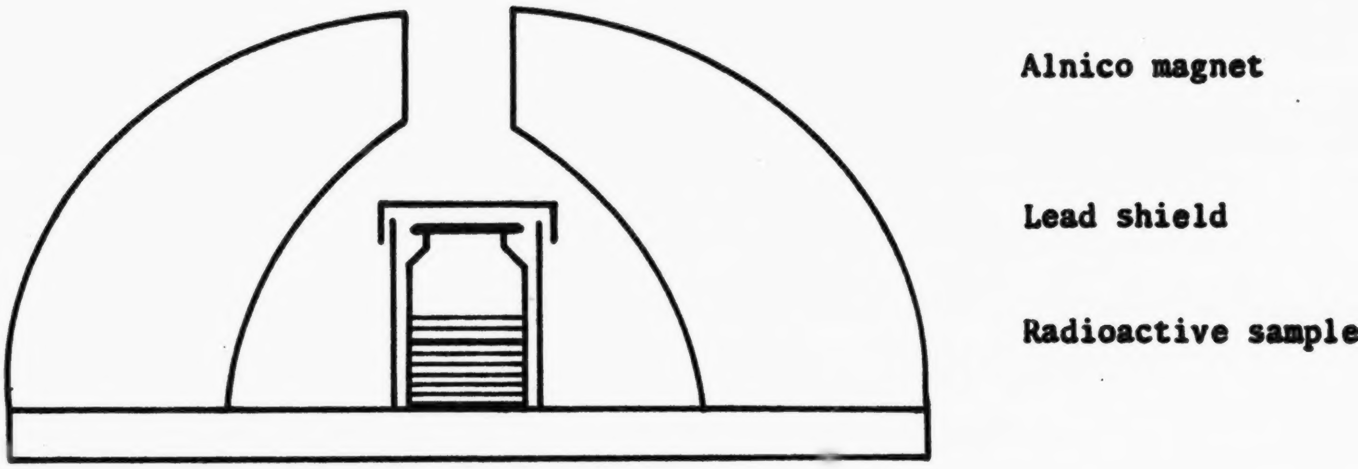
1. Arrange the counting equipment as indicated in Fig. 14-1.

2. Prepare a shield for the G-M tube by cutting a 0.5 cm wide slit 2 cm long in a piece of lead to shield the G-M tube.

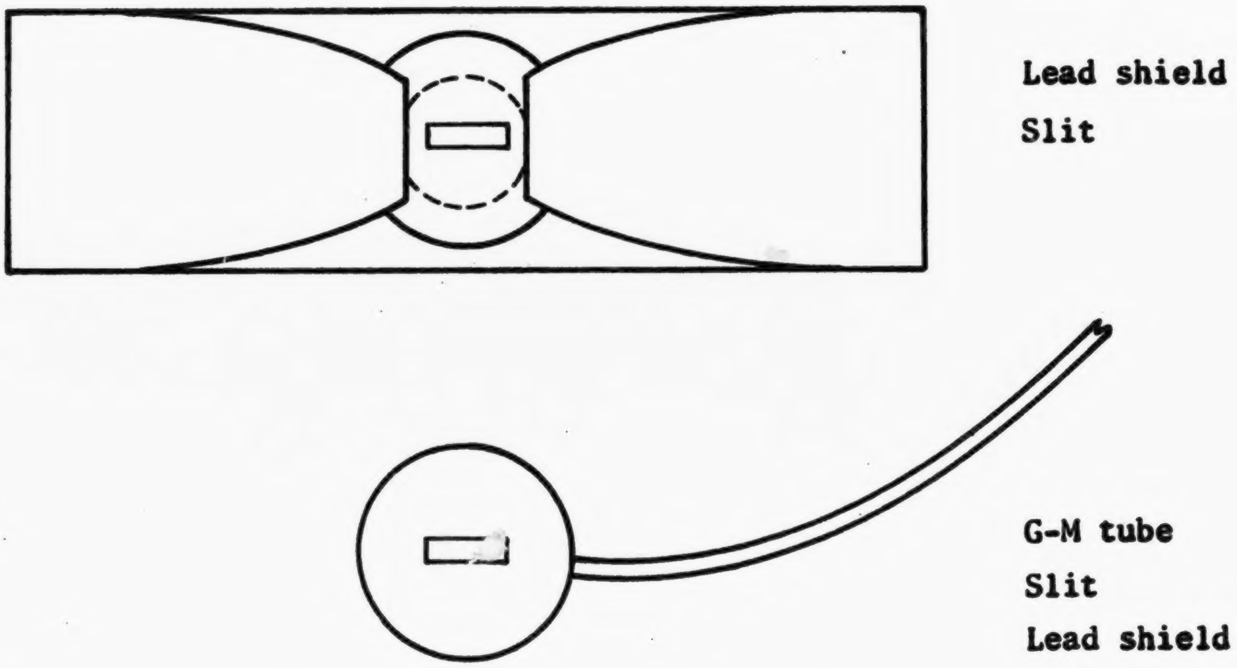
3. Prepare a similar slit for each of the containers holding the radioactive samples. Arrange the slit so that it is parallel to the magnetic field.

4. Place the bottle with the radioactive sample of phosphorus-32 so that a beam emerging from the slit will pass between the poles of the Alnico V magnet. The slit should be approximately the same height as the lowest section of the magnet.

5. Arrange the G-M tube on a suitable support so that it may be swung in an arc about the center of the magnet poles. Note that if the magnetic fields are uniform and extended, the beam comes to a focus at some point after completing exactly a semicircle. In this


Alnico magnet
Lead shield
Radioactive sample

Side view showing bottle of radioactive material, lead shield, and Alnico V magnet.


Lead shield
Slit
G-M tube
Slit
Lead shield

Top view showing magnet, sample, and G-M tube with 0.5 x 2 cm slits.

Fig. 14-1. Magnetic deflection set-up

event the probe should intercept the maximum activity with the slit face upward as the probe is moved horizontally away from the radioactive source. In the non-homogenous field the beam does not come into focus, and it is necessary to intercept the beam before it completes a semicircle.

6. Move the probe upward and rotate it, keeping in mind that the beam will make a curve to the left or the right, and find the location of the maximum activity.

7. Rotate the G-M tube so that the beam enters the window perpendicular to the lead shield. This point can be determined by an increase in the activity.

8. Record the direction in which the beam is deflected relative to both the magnetic field and the direction of motion of the beta particle.

9. Record the approximate angle of the deflection where the counting rate is greatest.

10. Reverse the magnet and note the direction in which the beam is now deflected.

11. Repeat the experiment using thallium-204. Since the beta particles from thallium have one-half the energy of the beta particle from phosphorus, is the deflection expected to be greater or less?

12. Record the angle and direction of deflection.

13. Repeat the experiment with sodium-22. Sodium-22 is a positron emitter with energy slightly less than the beta particle energy of thallium.

14. Repeat the experiment with iodine-131, a gamma emitter. Since iodine-131 also emits beta particles, what precaution is necessary to assure that beta particles are not recorded by the G-M counter?

15. Remove the containers holding the radioactive sources. Replace the beta ray with electrons flowing in a wire by inserting a wire into the magnetic field in the same direction as the original beam of beta particles. Connect the lower end of the wire to the negative pole of a 1.5-volt dry cell and momentarily touch the returning wire to the positive pole. The wire will deflect in the same direction as the deflection of the beta particle.

16. With the wire in place, reverse the battery connection so that the positive potential is connected to the bottom of the wire and see if the deflection agrees with the deflection found for positrons.

RESOURCE MATERIAL

Any charged particle moving in a magnetic field is deflected by the magnetic field. The force producing the deflection is proportional to the charge carried by the particle, the velocity of the particle, and the strength of the magnetic field. The force experienced by the charge is given by the equation

$$\text{Force} = \frac{evH}{c}$$

where e is the charge in e.s.u., v is the velocity in centimeters per second, H is the strength of the magnetic field in gauss, and c is the velocity of light in centimeters per second. The direction of the force is perpendicular to both v and H.

A more complete description of the force is given by

$$F = \frac{e(\overline{v} \times \overline{H})}{c}$$

where v and H are vector quantities having both magnitude and direction. The direction is determined from this equation by rotating the direction of $\overline{v}$ into the direction of $\overline{H}$. The direction is that direction in which a right-handed screw would progress if it were rotated in a direction from $\overline{v}$ to $\overline{H}$.

If the charge on the particle is negative, as is the case for a beta particle, a negative sign must be assigned to the charge e. This indicates that the direction is opposite of that given above. More specifically, if the experimental arrangement is assembled as diagrammed in Fig. 14-1, the north pole will be on the left side of the sample. The direction of the magnetic field H is now defined as the direction starting with the north pole and going to the south pole, or from left to right. The velocity, on the other hand, is in the upward direction. If a right-handed wood screw is rotated from the vertical upward direction to the right-hand direction, the rotation is clockwise when observed from in front of the apparatus. The screw, therefore, progresses to the back of the work space. Consequently, a particle carrying a positive charge is deflected toward the back of the work space while a negative charge is deflected forward from the source. It is thus possible to differentiate between positrons and beta particles, or particles carrying positive and negative charges, by observing the direction of deflection as given by this equation.

It is possible to verify this phenomenon experimentally by replacing the electron beam with a wire carrying an electric current. If the wire is connected to a battery, say a 1.5-volt dry cell, electrons may be thought of as flowing from the negative pole to the positive pole. If such a wire is placed in the magnetic field to replace the beam of beta particles, the end of the wire connected to the negative pole should be fastened to the bottom plate of the magnet and the wire should extend upward through the magnetic field and thence to the positive pole of the battery. The wire may be positioned by attaching the wire to two insulated clamps, preferably wooden clamps, so that the clamping arrangement is not affected by the strong magnetic field.

In order to note the effect on the wire, the positive end should momentarily be touched to the positive terminal of the battery. The wire is then deflected in the direction in which the beta particle is deflected.

If the terminals on the battery are reversed, making positive connection to the lower wire with current direction from positive to negative upward through the magnetic field and thence to the negative terminal of the battery, the current in the wire is identical to the positrons emitted by sodium-22. The wire, consequently, is deflected in the direction in which the positrons are deflected.

If the experiment is restricted to particles having a single electron charge, then the force is proportional to the velocity and the magnetic field.

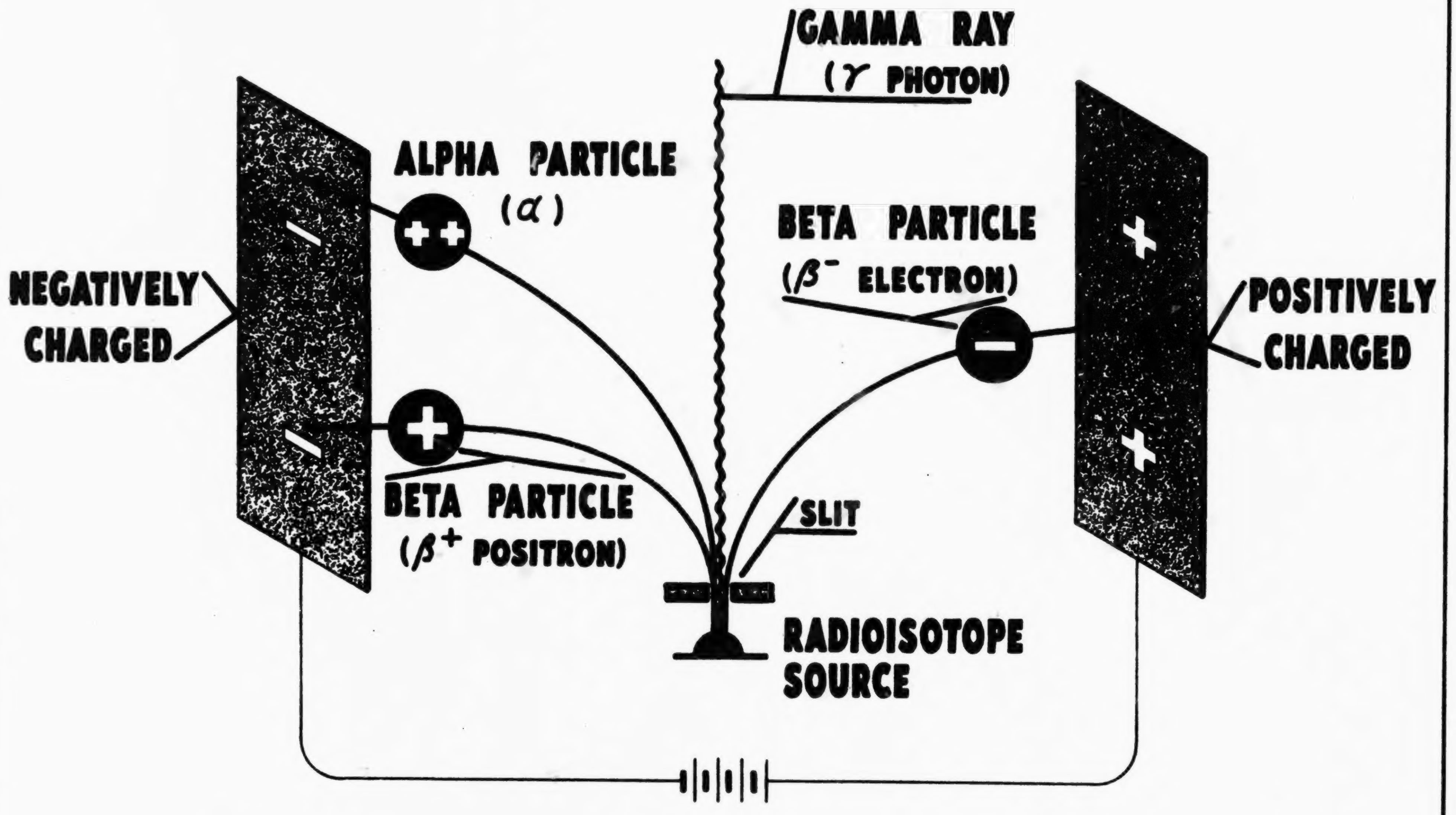
It can be shown that particles leaving the slit with uniform energy make one-half revolutions and come to an approximate focus some distance from the source. The radius of the semicircle the particles make is a function of the mass of the particle, the charge of the particle, the energy of the particle, and the magnetic field. Again for beta particles and positrons, the radius is a function only of the energy and the magnetic field: the greater the energy, the larger the radius; the greater the magnetic field, the smaller the radius.

If the energy of the particle is in the region of 1,000 ev, a simple relationship can be written for this

$$E_{ergs} = 8.8 \times 10^{-8} r^2 H^2$$

Beta particles with energies in the vicinity of 1 Mev have velocities that approach the velocity of light, and it is necessary to make corrections for the relativistic effect or the increase in apparent mass as the velocity increases. Furthermore, in order to solve the problem, it is necessary to know the magnetic field in gauss and to have an extended magnetic field. For this reason, no estimate will be made about the energy of the particle except to determine that the radius of curvature for thallium-204 is less than the radius

ELECTRICAL PROPERTIES OF RADIATIONS


GAMMA RAY
(γ PHOTON)
ALPHA PARTICLE
(α)
BETA PARTICLE
(β^- ELECTRON)
NEGATIVELY CHARGED
POSITIVELY CHARGED
BETA PARTICLE
(β^+ POSITRON)
SLIT
RADIOISOTOPE SOURCE

of curvature for phosphorus-32. Likewise, some estimate can be made of the energy of the sodium-22 positron on the basis of the observed deflection of the particle from the vertical.

While it is possible to find such beta emitters as phosphorus-32 and thallium-204 that emit no gamma rays, all of the common positron emitters also emit gamma rays. The readings of the activity as a function of deflection for sodium is clouded by the fact that gamma rays are likewise emitted, some penetrating through the lead shielding, and some being recorded in the counter. The point of maximum deflection, therefore, is difficult to determine, but an increase in the counting rate can be noted in the opposite direction from that of the beta particle. Iodine-131 is also a beta and gamma emitter, but simple shielding at either the source or around the G-M tube eliminates the beta particles that would otherwise reach the tube.

QUESTIONS

1. Give the equation for attraction forces between charged particles.
2. Give the equation for the force experienced by an electrical charge moving in a magnetic field.
3. If the charge is 4.8×10^{-10}, the velocity is 10^9 cm per second, and the magnetic field is 20,000 gausses, what is the force in dynes?
4. How is the direction of the force of a negative charge moving in a magnetic field determined?
5. What is the direction of the force on a positive charge moving in a magnetic field?
6. Since the alpha particle has two positive charges and approximately two hundred times the mass of the beta particle, would the alpha particle be deflected more or less than the beta particle?
7. Describe the focusing of the beam by a magnetic field when the beam originates at a slit.
8. Why is the beam in this experiment not strongly focused?
9. Since iodine-131 emits beta particles as well as gamma rays, what precaution is necessary to assure that beta particles are not recorded by the G-M counter when making measurements on gamma rays?
10. If the energy is larger, is the radius of curvature greater or less for beta particles? Assume the magnetic field does not vary.
11. How does the radius of the curvature vary with the magnetic field?

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15

comparison of g-m, gas flow proportional, and scintillation counters

PLAN OF INSTRUCTION

OBJECTIVE

1. To study the behavior of the proportional counter.
2. To study the behavior of the scintillation counter.
3. To use the proportional counter as a means of discriminating against beta and gamma radiation and to count alpha particles only.
4. To arrange a scintillation counter set-up that is sensitive to gamma rays only and insensitive to beta and alpha particles.
5. To compare the efficiency of the G-M and proportional counters for alpha and beta sources.
6. To compare the efficiency of the G-M and scintillation counters for gamma sources.

INTRODUCTION

1. Review the operation of the G-M counter.
2. Review the relationship between the charge collected as a function of collection voltage and stress the various counting regions
    a. The region in which the counter operates as an ionization chamber
    b. The region in which the counter operates as a proportional counter
    c. The region in which the counter operates as a G-M counter
    d. The region of multiple counts
3. Review the function of the quenching gas and the reason why the quenching gas is not required in the gas flow proportional counter.

TEACHING PLAN

1. The G-M counter operating on the counting plateau is activated by a single ionized particle, even by a photo electron ejected from the walls of the counter by a photon.
2. As the voltage is reduced to below the Geiger plateau, the G-M counter operates in the proportional region, a region in which the intensity recorded by the electrical current is proportional to the initiating ionization.
3. Effective counters that measure ionization utilize gas at slightly above atmospheric pressure.
4. The nuclide to be counted can be placed directly in the chamber, thereby avoiding errors due to absorption in air and in the counting window. Purpose of the flow of gas is to assure the purity of the counting gas in the system. Only a minute amount of gas flows through the counter.

5. Scintillation counters utilize the scintillation, or flash of light, produced when radiation is absorbed in certain crystals and liquids.
6. Photomultiplier tubes are used to amplify the current produced by the primary photocell.
7. The output signal of the photomultiplier tube is proportional to the intensity of scintillation and, consequently, the ionization produced by radiation.
8. Liquid scintillators can be employed and the radioactive material can be mixed directly into the liquid, thereby producing a very efficient count.
9. Quenching circuits are not required in the case of the scintillating counter.
10. High-gain, lineal amplifiers (called proportional amplifiers) are used with gas counting systems and with scintillation counting systems.

APPARATUS

G-M tube with rack to hold tube and sample

G-M scaler with variable voltage control

Timing system, such as a timer or clock

Flow counter

Scintillation counter

Proportional amplifier

Alpha source

Beta source

Gamma source

Counting gas and flow regulator

EXPERIMENTAL PROCEDURE

1. Arrange the G-M tube for a specific separation between the window of the counter and the sample, and make a series of counts to establish a ratio of the recorded counts of the alpha, beta, and gamma sources.
2. Arrange the gas flow counting apparatus and repeat the series of counts on the same sample, using the gas flow counter.
3. Assemble the scintillation counter equipment and repeat the counting procedure, using the scintillation counter.
4. Shield the scintillation counter with a sheet of 1/16-inch lead to block out any alpha and beta rays and repeat the series of counts.
5. Tabulate the activity for the four types of counts as a function of the types of sources.
6. If an oscilloscope is available, observe the pulse heights produced by the G-M counter, the gas flow counter, and the scintillation counter.

RESOURCE MATERIAL

In addition to the G-M counter, several other counting systems are available and perform specific tasks more effectively than the G-M counter.

When the G-M counter is adjusted to the counting plateau, it produces a series of pulses of equal height regardless of the number of ion pairs in the initial ionization. Thus, even a single electron ejected by a photon, referred to as a photoelectron, can originate the ionization necessary to produce a maximum height pulse in a G-M counter. For this reason, certain tubes are painted black or enclosed in an opaque enclosure to prevent visible and ultraviolet light from initiating counts. Obviously then, the counter will not discriminate against alpha, beta, or gamma rays.

The G-M counter may be operated in the proportional region by reducing the voltage to a point below the Geiger point. Under this circumstance, the counter is sensitive to ionization and produces pulse heights that are proportional to the initiating ionization. By observing such pulses on an oscilloscope, it is possible to identify alpha particles, beta particles, and gamma particles by observing the height of the pulses produced.

One of the obvious drawbacks of the G-M tube used as a proportional counter is that absorption in air between the source and the counter window and absorption in the counter window reduces the effectiveness of the device for alpha counting. This objection can be overcome by arranging a counting system that operates at atmospheric pressure. Since air is not effective as a gas in a counting tube, special gases are available for this type of operation.

The detection chambers for gas flow counters consist of a negatively charged holder with a positively charged plate that is usually positioned above a base plate. The radioactive sample is placed on a suitable planchet that fits on the base plate, and the ionization produced in the gas is collected by the positively charged collector plate. A very small amount of gas is passed into the system and a sufficient amount of pressure is used so that the gas entirely displaces the air in the counter chamber.

A common gas used for gas counting (Atomic Accessories, Inc., Model FPG-39 Proportional P-10 counting gas) consists of 90% argon and 10% methane. Another gas, consisting of 99% helium and 1% isobutane, is known as Geiger counting gas and is suitable for gas counting.

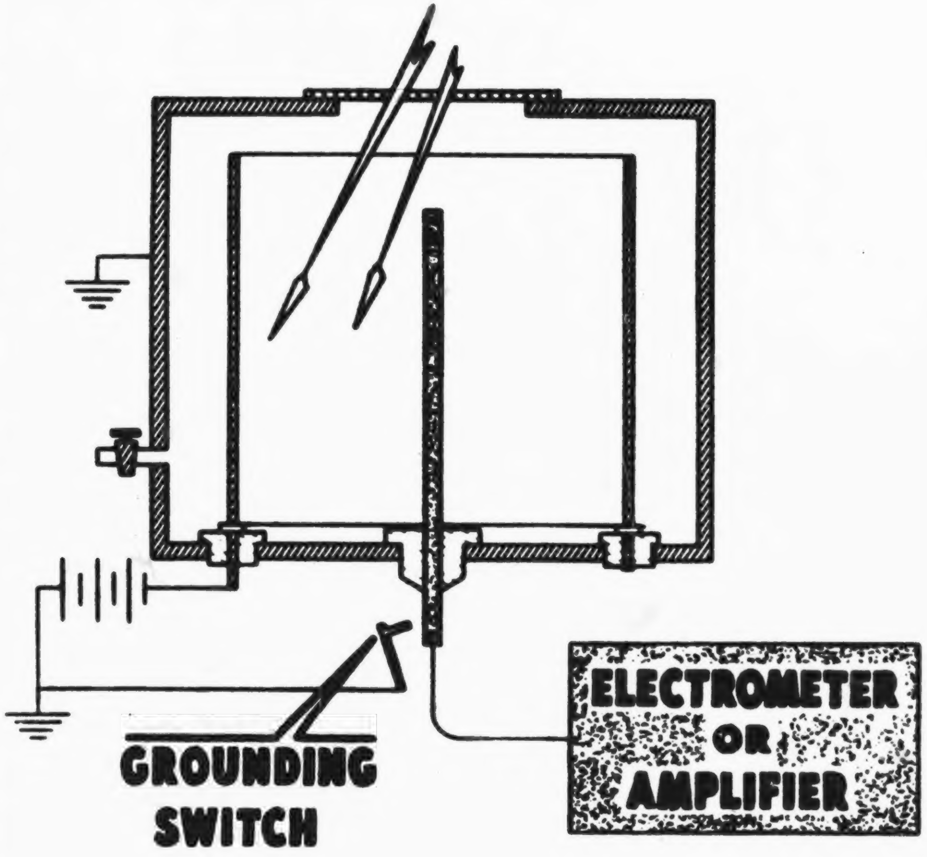
The ionization produced in gases at atmospheric pressure by beta and gamma rays is much larger than the initial ionization produced in a G-M tube with less than 10 percent atmospheric pressure. Ionization is proportional to the number of gas molecules per unit volume. Because of this, the windowless gas flow counter is especially suited for counting low energy or soft beta rays as emitted by carbon-14, sulfur-35, or calcium-45. Furthermore, the windowless gas counter is the most efficient counter for alpha particles, especially those particles with an energy level below 2 Mev.

When the pulse heights produced by the pulses in a gas flow counter are observed on an oscilloscope, there is a great variation in the pulse height. Gamma particles are hardly observable. Beta particles register as pulses approximately 1 percent as high as alpha particles.

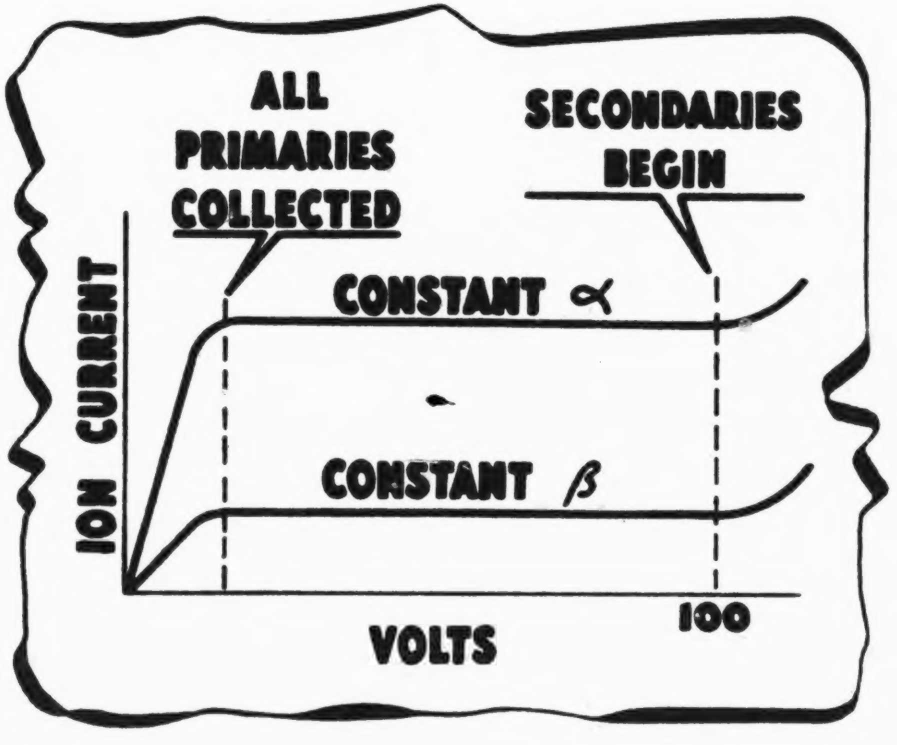
Gas flow apparatus can be effectively used in the spectra analysis of beta rays. Since pulse height is proportional to initial ionization produced by the beta ray, a pulse height analyzer can be employed to count only those beta rays that fall within a range of energies. The pulse height analyzer can be made to discriminate against beta rays above and below a pre-set value. For instance, the region of acceptance can be made as narrow as .1 Mev and the spectra of energy can be examined to determine the relative number of beta rays of each energy level that are emitted by the nuclide. This technique is referred to as beta ray spectroscopy.

In performing experiments with gas counting equipment, the sample is placed in the gas flow counter, the voltage is set to the approximate counting voltage, and the gas flow is started.

THE IONIZATION CHAMBER



ELECTROMETER
OR
AMPLIFIER
GROUNDING
SWITCH



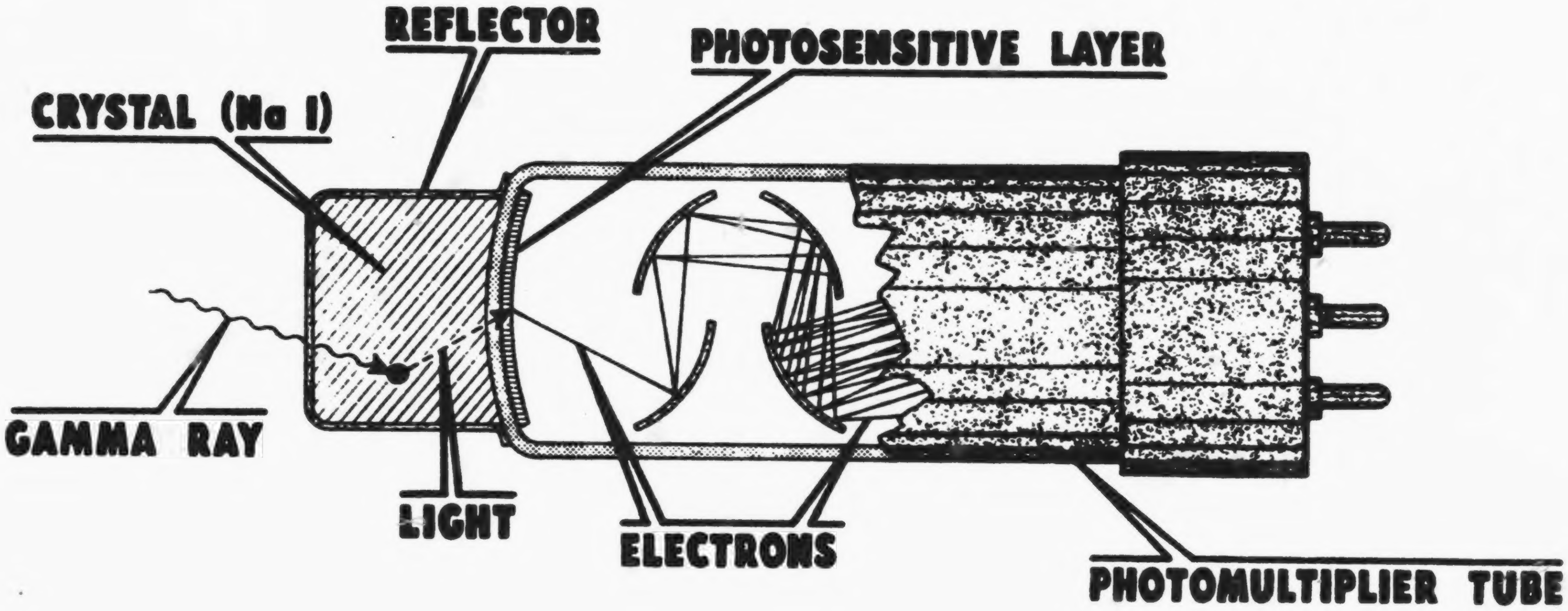
. SENSITIVE TO ALL RADIATIONS

. LOW-ACTIVITY CAN BE MEASURED — — BUT

..AUXILIARIES EXPENSIVE

..ADJUSTMENTS DIFFICULT

SCINTILLATION COUNTER


REFLECTOR
PHOTOSENSITIVE LAYER
CRYSTAL (Na I)
GAMMA RAY
LIGHT
ELECTRONS
PHOTOMULTIPLIER TUBE

TOTAL LIGHT TO TUBE NEARLY PROPORTIONAL TO GAMMA RAY ENERGY

IF 1 ELECTRON EJECTS 5 FROM A DYNODE, 11 DYNODES RESULT IN 5^{11}
OR
ABOUT 50 MILLION ELECTRONS OUTPUT

It will be noted that when the chamber is filled with air the pulse heights are either very low or missing entirely. As the air is forced out of the chamber and the pure gas fills the chamber, the pulse heights increase and become stable.

Scintillation counting is the oldest of the various types of counting methods. It was first used by Becquerel when he discovered that a crystal of zinc sulfide emitted a flash of light when struck by an alpha particle. This phenomenon is known as a scintillation. A screen made of zinc sulfide with a small copper impurity can be effectively used to count alpha rays and is almost entirely insensitive to beta rays and gamma rays. Such a counter is usually observed by a magnifying glass or a 30-power microscope.

More effective scintillation counters are made by crystals of thallium-activated sodium iodide one cubic inch or larger. Such crystals have the advantage that all of the energy of the beta rays entering the crystal will be converted to a scintillation, and much of the energy of the gamma ray will be converted to a scintillation. Consequently, the scintillation process is extremely effective in detecting alpha, beta, and gamma rays. The counter is most efficient for gamma rays, and it is the only effective simple laboratory device for measuring gamma rays.

The light produced by the minute scintillation is transmitted to a photoelectric multiplier tube. In most cases the crystal is cemented to the tube to prevent any loss of light between the crystal and the tube.

The photomultiplier tube and the crystal are mounted inside a metallic cylinder so that no outside light whatsoever enters the enclosure. The other five sides of the crystal are sometimes silver-plated to reflect all of the light into the photoelectric tube. Since the metallic shield effectively absorbs alpha and beta rays, the enclosed scintillation counter is sensitive only to gamma rays.

The pulse heights produced by the scintillation counter are proportional to the energy lost by the ray. While the gamma ray may not be totally absorbed into the crystalline material, all of the energy of the beta ray and alpha ray is absorbed into the scintillation material. Proportional analyzers and oscilloscopes may be added to observe the pulse height. Pulse height discriminating equipment can be used to identify alpha and beta particles as a function of their energies.

Scintillation counters using liquids for the scintillation material are especially useful for counting low-energy alpha particles, as well as beta and gamma particles. A series of liquids have been developed that exhibit the same scintillation properties as the sodium iodide crystal and zinc sulfide. Many preparations may be dissolved in solvents and added directly to the scintillation liquid; counters of this type will accurately count all of the disintegrations produced in the liquid. The obvious advantage is that complex corrections for losses in counts need not be made.

Another advantage of scintillation counting is that a quenching mechanism is not required; thus, the system has no dead-time. Two minor sources of error still exist: the loss of rays that are produced at the boundary between the metal and the liquid; the coincident counts, or the loss of a count when two disintegrations occur at the same instant.

QUESTIONS

1. Describe the operation of a G-M counter when it is operating below the Geiger plateau.
2. What is the characteristic of the counter when it is operating on the counting plateau?
3. Describe an arrangement that will measure the ionization at atmospheric pressure.
4. What is the purpose of the "flow" of the counting gas?
5. What special precaution must be used to prevent contamination in a gas flow counter?
6. What is the purpose of the photomultiplier tube in a scintillation counter set-up?
7. Where does the primary current pulse originate in the scintillation counter?

8. What is the advantage of a liquid scintillation counter over a solid scintillation counter?
9. Justify the lack of quenching circuits in the scintillation counter.
10. What is the purpose of the proportional amplifier?
11. Give the composition of a suitable gas for use in gas flow counting.
12. Why are some G-M tubes coated with an opaque paint?
13. What is the advantage of placing the radioactive sample to be counted inside the G-M tube?
14. What type of crystal is used in the scintillation counter?
15. How would you arrange a scintillation counting system to be sensitive only to gamma rays?

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16

radioactive fallout

PLAN OF INSTRUCTION

OBJECTIVE

1. To become familiar with the phenomenon of fallout in the atmosphere.
2. To study nuclear fission and the formation of radioactive fallout particles.
3. To learn the standardized tests used to measure fallout in rain.
4. To collect radioactive dust for counting purposes.
5. To initiate a program of continuing monitoring of radioactive dust and fallout.
6. To learn the photographic techniques for detecting radioactive particles.

INTRODUCTION

1. Discuss the presence of natural radioactive isotopes in the atmosphere, such as carbon-14, potassium-40, and radon-222.
2. Introduce the concept of the presence of induced radioisotopes due to nuclear devices.
3. Review the characteristic of beta emitting nuclides, nuclides that have an excess number of neutrons. Refer to Fig. 2-1.

TEACHING PLAN

1. Atomic bomb explosions in the atmosphere have led to great concern over fallout of radioactive material.
2. Fallout particles are either particles of the original material that did not undergo fission or fission products.
3. Nuclear fission occurs generally in atoms whose atomic number is greater than 90.
4. For practical consideration, uranium-233, uranium-235, and plutonium-239 are used for reactions involving fission.
5. Nuclear fission occurs when a fissionable atom absorbs an additional neutron and becomes so unstable that it disintegrates into two fragments.
6. The fragments so produced have an excess of neutrons and, consequently, are beta emitters.
7. A whole series of elements located approximately in the middle of the atomic table are produced by fission.
8. When a nucleus undergoes fission, it divides into two fragments of unequal mass; the smaller group clusters around a mass number of 94, and the larger group clusters around a mass number of 136.

9. In the fission action, an average of 2.3 neutrons are produced.

10. Fission takes place roughly within 10^{-12} seconds after a neutron is captured by the fissionable nuclide.

11. A total of approximately 200 Mev of energy is released by each atom undergoing fission.

12. Approximately 90 percent of the energy is released at the time of fission and the remaining 10 percent is subsequently released as beta particles.

13. The fission fragment usually undergoes a chain of from three to six beta decays before becoming stable.

14. Most of the half-lives of the fission products are less than sixty days but one, technetium-99, has life of 2.12×10^5 years.

15. Since for equal amounts of radioactive material, the ones with short half-lives have the greatest activity, the greatest danger exists in the first few days after a fissionable reaction has occurred.

16. Gamma rays accompany almost all of the beta reactions and are the greatest health hazard because of their range and ability to penetrate shielding.

17. The standard sample for measuring fallout in rain water is the residue from 500 ml of rain water.

18. Dust samples can be collected, but it is difficult to standardize such collections.

APPARATUS

End-window G-M tube with rack to hold tube and sample

G-M scaler with variable voltage control

Timing system, such as a timer or clock

Basin to collect rain water

Small centrifugal blower

X-ray film

X-ray film holder

EXPERIMENTAL PROCEDURE

Fallout in Rain Water

1. Collect 500 ml of rain water in a suitable container and evaporate the water slowly over a bunsen burner.

2. Transfer the residue to a planchet and repeatedly wash the evaporating container until all of the radioactivity has been transferred to the planchet.

3. Dry the planchet under a heat lamp and spray with a very thin film of collodium to prevent loss of the fallout particles.

4. Make a series of counts extending over several weeks on the sample.

5. Absorb the beta rays by a suitable aluminum absorber and count the gamma rays.

6. Subtract the gamma rays from the beta ray count to get the net beta ray counts.

Fallout in Dust

1. Blow air through a fine glass wool filter for a period of twenty-four hours. The air should be taken from the outside atmosphere, although samples obtained in laboratory rooms have proven satisfactory.

2. Place the glass wool sample directly in front of the end-window counter and make a series of readings, again extending over several weeks.

3. Using an aluminum absorber, filter out the beta particles and count the gamma rays alone.

4. Plot the activity on a semi-log graph. If a single half-life nuclide was responsible for the radiation, the curve would be a straight line. Since the curve will approach zero activity asymptotically, this indicates that several half-lives are involved.

5. Draw a line that will fit underneath the curve where the activity is the greatest. This straight line will approximate the shortest half-life nuclide among the fallout fragments.

6. Similarly, a line drawn underneath the curve as it approaches zero activity will give some idea of the longest half-life of the nuclide present.

Photographic Determination of Fallout Particles

1. Collect a suitable amount of fallout in rain water. If there has been no rain, dust may be dissolved in distilled water.

2. Filter the resulting fallout in water solution through a filter paper and dry the paper in air or under a sun-lamp.

3. In a dark room insert the paper in a film holder loaded with X-ray film and set the film holder aside for one week.

4. Develop the film with X-ray developer and a fixer solution.

5. Cut the film into a number of small sections and observe the darkened spots produced by the radioactivity. The film may be examined under a low-power microscope.

6. Tiny blackened spots are produced by beta rays and star shaped images are produced by the more active alpha particles coming from unspent fission material.

RESOURCE MATERIAL

Radioactive fallout is usually meant to include only those radioactive materials that result from a nuclear device, usually a bomb exploaded in the atmosphere. Debris from a nuclear explosion contains unspent initial matter as well as fragments from the explosion.

Certain other sources of fallout have always existed. A small amount of radium and its daughter, radon-222, is continually in the air. Carbon-14, a beta active element, is formed by the action of cosmic-ray-produced neutrons on nitrogen nuclei high in the atmosphere. The constant production of this nuclide keeps the ratio of carbon-14 to stable carbon at a constant value. Potassium-40 is a naturally radioactive element that is present in all rock. Tritium, an isotope of hydrogen, is produced by cosmic-ray-initiated neutrons on nitrogen and contributes to the total. The half-life of the naturally radioactive isotopes found in the atmosphere is very long, and the activity would not be found to vary in the time available for experiments on these nuclides.

The half-lives of radioactive elements produced by nuclear devices, on the other hand, are very short and decrease in their activity is marked. It is, therefore, possible to obtain a change in a reading in a very short period of time. Radioactive fallout may be collected by a number of methods: by collecting dust on a sticky paper exposed to the atmosphere for a period of a day, by placing a large plastic sheet on a roof and washing the dust carefully into a beaker with water, by collecting a rain water sample and evaporating the water, and by collecting dust from filters of various types.

The fallout fragments contained in rain water are measured by collecting 500 ml of rain water, carefully evaporating the water, and concentrating the fallout on a planchet. The total activity in microcuries per 500 ml can be estimated by the number of counts per minute and by the relations given for the disintegration per second in Session 4. Care must be taken to make all of the corrections for such counting errors as the function of backscattering, absorption, coincident counts, and dead-time.

When a filter is used for collecting samples, only a fraction of the original activity is captured by the filter. The effectiveness of the filter can be determined by blowing air through two similar filters and counting the activity on the two filters separately, N_1 and N_2. If the actual activity is given by A and the fraction of the material that adheres to a filter is given by x, then

$$N_1 = Ax$$

The second filter would receive a total of $A - N_1$ particles and would filter out a similar fraction x. Therefore,

$$(A - N_1)x = N_2$$

These two equations may be solved to give

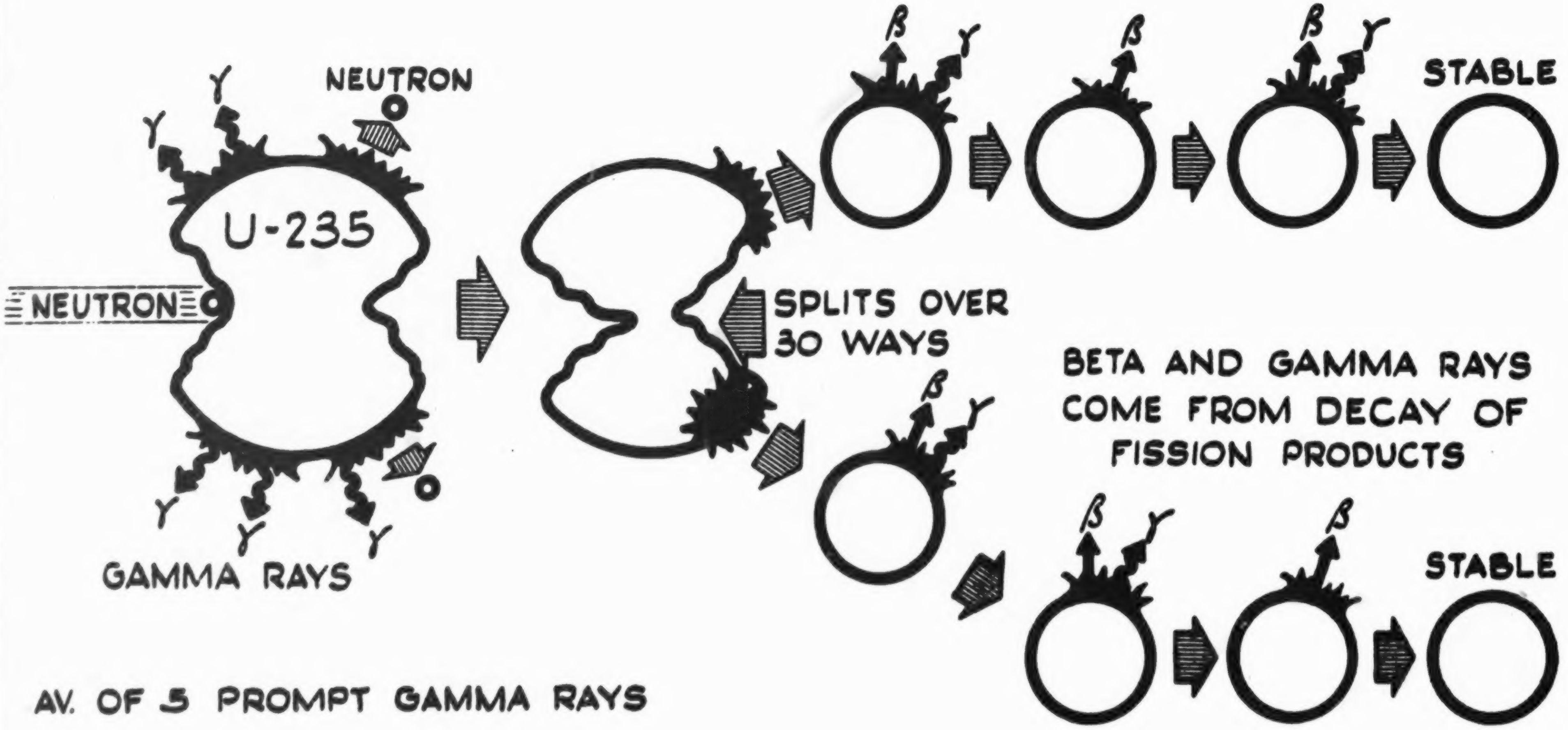
$$A = \frac{N_1^2}{N_1 - N_2}$$

For example, if a total of 1,280 counts are observed for the first filter and the second filter records activity of 860, the total number of particles, A, is 3,880, and the effectiveness of the filter x is 1/3, or 33 percent. It is thus possible to estimate the total activity from an observed partial recovery.

Photographic plates have proven to be very useful for the purpose of observing radioactive disintegrations. X-ray plates are designed especially to be sensitive to X rays and also sensitive to beta and alpha rays. Radioactive samples may be deposited on a filter paper and enclosed with the radioactive material adjacent to the emulsion side of the X-ray film. The film holder may then be closed and the film left for a week. Small spots 1/100 mm or larger indicate the disintegration of a beta emitting nuclide. Larger star shaped spots indicate the disintegration of an alpha emitting nuclide. It is possible to determine the activity of the sample by counting the number of spots recorded on the photographic paper and, to the first approximation, multiply the spots by two on the assumption that half of the rays penetrated the X-ray film and the other half were absorbed by the film holder.

When uranium-235 atom absorbs a neutron, the nuclide becomes violently active. Within a time estimated to be in the vicinity of 10^{-12} seconds, the nuclide breaks into two fragments, one slightly larger than the other, with a release of approximately 160 Mev. The two fragments are not the same size, nor are they identical in each reaction. Figure 16-1 gives the observed percentage fission yield for uranium-233, uranium-235, plutonium-239, and for atomic numbers between 70 and 160. Table 16-1 gives the breakdown for the long-lived fission products of high yield for the light group and for the heavy group.

Uranium Fission Process


γ
γ
NEUTRON
U-235
NEUTRON
γ
γ
γ
GAMMA RAYS
SPLITS OVER
30 WAYS
β
γ
β
β
γ
STABLE
β
γ
β
γ
β
STABLE

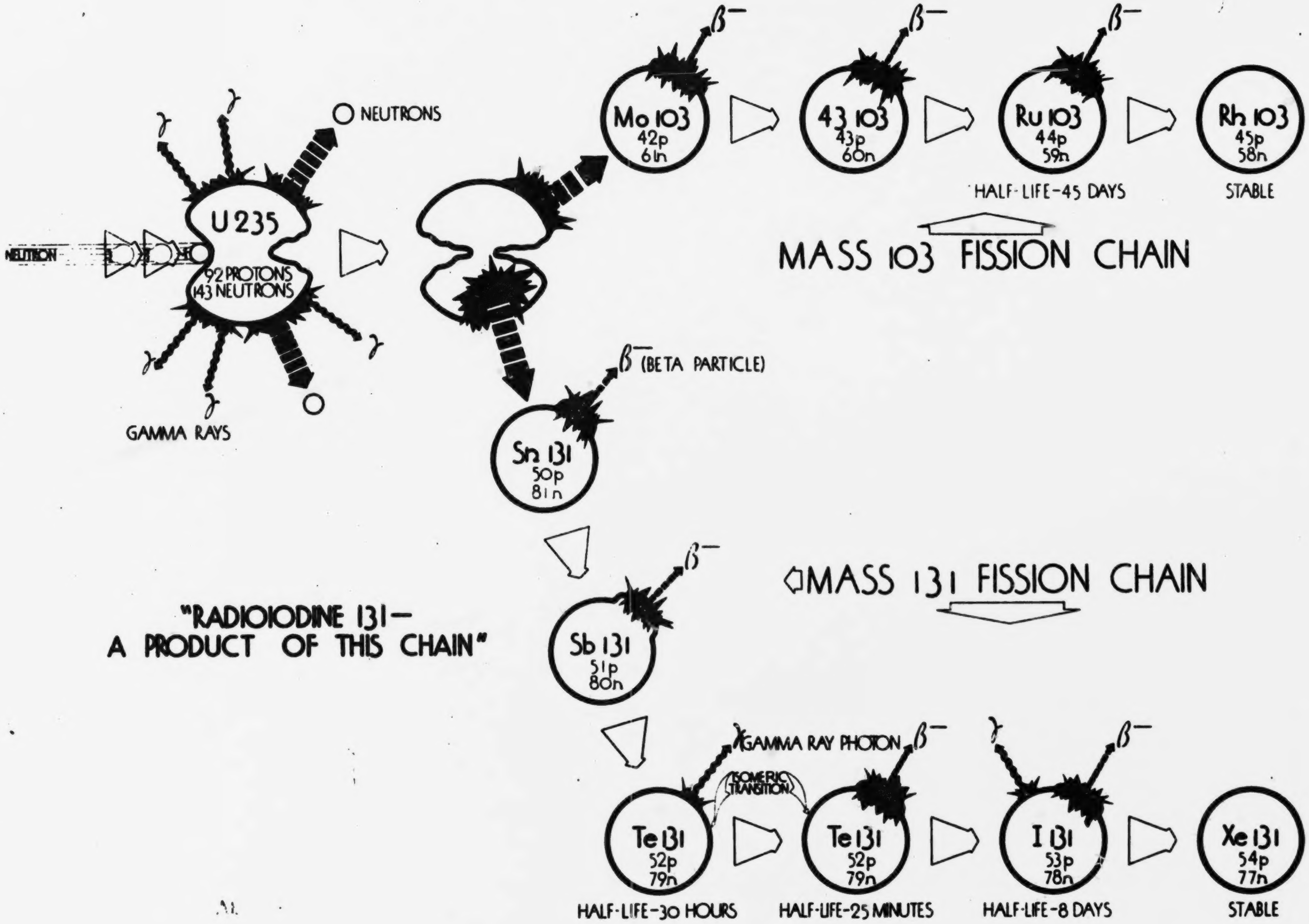
BETA AND GAMMA RAYS
COME FROM DECAY OF
FISSION PRODUCTS

AV. OF 5 PROMPT GAMMA RAYS

AV. OF 2.5 NEUTRONS
(99% PROMPT, 1% DELAYED)

. FISSION PRODUCTS TOTAL ABOUT
  200 RADIOACTIVE SPECIES.
. ATOMIC NUMBERS 30 TO 64
. MASSES 72 TO 161
. (Zn 72 TO Gd 161)

URANIUM FISSION AND BETA CHAIN DECAY


NEUTRON
U 235
92 PROTONS
143 NEUTRONS
NEUTRONS
GAMMA RAYS
γ
β^-
β^- (BETA PARTICLE)
Mo 103
42p
61n
43 103
43p
60n
Ru 103
44p
59n
HALF-LIFE-45 DAYS
Rh 103
45p
58n
STABLE
MASS 103 FISSION CHAIN
Sn 131
50p
81n
Sb 131
51p
80n
MASS 131 FISSION CHAIN
γ GAMMA RAY PHOTON
ISOMERIC TRANSITION
Te 131
52p
79n
HALF-LIFE-30 HOURS
Te 131
52p
79n
HALF-LIFE-25 MINUTES
I 131
53p
78n
HALF-LIFE-8 DAYS
Xe 131
54p
77n
STABLE

"RADIOIODINE 131—
A PRODUCT OF THIS CHAIN"

In addition to the light and heavy fragments that are produced, from two to three neutrons are simultaneously released. Referring to Fig. 2-1, the position of the two fragments can be estimated by drawing a straight line between the position of the element with atomic number 92 and the zero point. Any division of the uranium atom results in two nuclides in the region of excess neutrons.

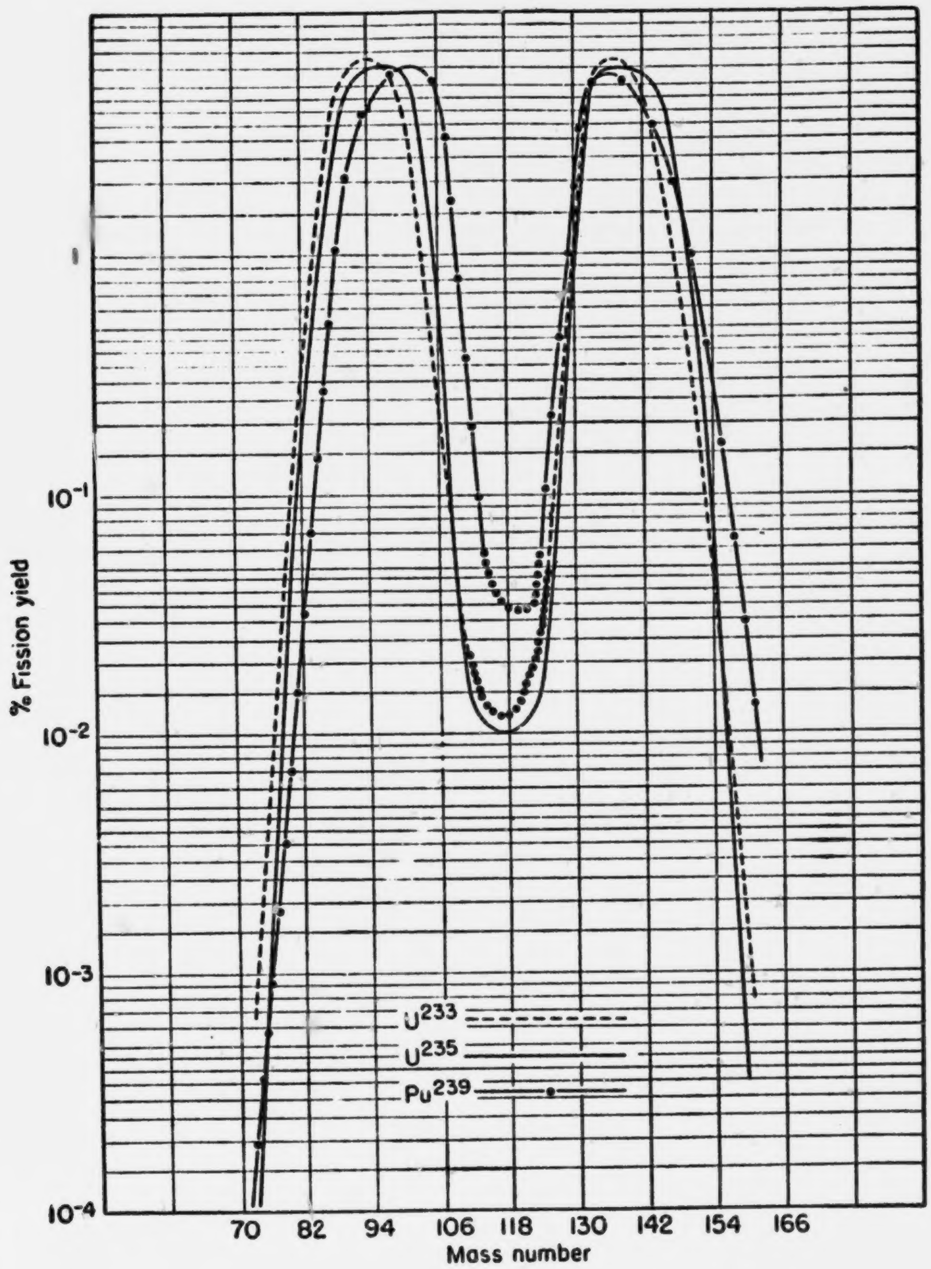


Fig. 16-1. Observed percent fission yield for U-233, U-235, Pu-239, and for atomic numbers between 70 and 160. (From Nuclear Radiation Physics by R. E. Lapp and H. L. Andrews. 3d ed. Copyright 1963. Prentice-Hall, Inc., Englewood Cliffs, N. J. Used by permission)

Nuclides that are not listed in Fig. 2-1 are radioactive, and nuclides that have an excess of neutrons are beta emitters. Both of the fission fragments, therefore, emit a series of beta particles with various half-lives until they reach a stable state. Depending upon the exact nuclide fragment, from three to five radioactive disintegrations take place before the nuclide reaches stability. Figure 16-2 shows a neutron being absorbed by uranium-235, the subsequent disintegration into krypton-90 and barium-143, and a series of four subsequent disintegrations resulting in the stable isotopes zirconium-90 and neodymium-143.

Table 16-1
LONG-LIVED FISSION PRODUCTS OF HIGH YIELD

Fission product	*Fission yield, %*	*Half life*	*Beta energy,* Mev	*Gamma energy,* Mev
Light group:				
Kr^{85}	0.24	9.4 yr	0.695 0.15	0.54
Sr^{89}	4.6	53 days	1.463	none
Sr^{90}	5.3	19.9 yr	0.61	none
Y^{91}	5.4	61 days	1.537	1.2; 0.2
Zr^{95}	6.4	65 days	0.84 0.371	0.721
Tc^{99}	6.2	2.12×10^5 yr	0.290	none
Ru^{103}	3.7	39.8 days	0.698 0.217	0.498
Ru^{106}	0.5	1.0 yr	0.39	none
Heavy group:				
I^{131}	2.8	8.14 days	0.815 0.608 0.335 0.250	0.722; 0.637 0.608; 0.364 0.284; 0.080
Xe^{133}	6	5.27 days	0.345	0.08
Cs^{137}	6.2	33 yr	0.523 1.2	0.662
Ba^{140}	6.1	12.8 days	1.022 0.480	0.537; 0.304 0.162; 0.132; 0.030
Ce^{141}	6	33.1 days	0.581 0.442	0.145
Pr^{143}	6	13.8 days	0.932	none
Ce^{144}	5.3	282 days	0.300 0.170	0.033; 0.054 0.081
Nd^{147}	2.6	11.3 days	0.38 0.60 0.83	0.520; 0.391; 0.309 0.092
Pm^{147}	2.6	2.6 yr	0.223	none

(From Nuclear Radiation Physics by R. E. Lapp and H. L. Andrews. 3d ed. Copyright 1963. Prentice-Hall, Inc., Englewood Cliffs, N. J. Used by permission)

In addition to the beta particles emitted by the radioactive decay chain, gamma radiation accompanies most of the disintegrations. The energy of gamma radiation for some of the long-lived fission products is given in Table 16-1.

It is generally simple to provide a shield against beta particles. The inside of houses are usually adequately shielded by the shingle and wood in the roof, the air space in the attic and the plaster ceiling, and the air between the ceiling and the occupants. Refer to Session 7 for details on the absorption of beta particles and calculate the mg/cm^2 for the material in a typical home.

Gamma rays pose a serious health hazard, because they are not absorbed by the usual materials found in a home. Furthermore, any absorber only decreases the radiation rate by a fixed percentage. Since the gamma ray does not have a fixed range, it is impossible to filter out all the radiation.

The student should measure the background count and refer to Session 4 to see if the present background is a health hazard.

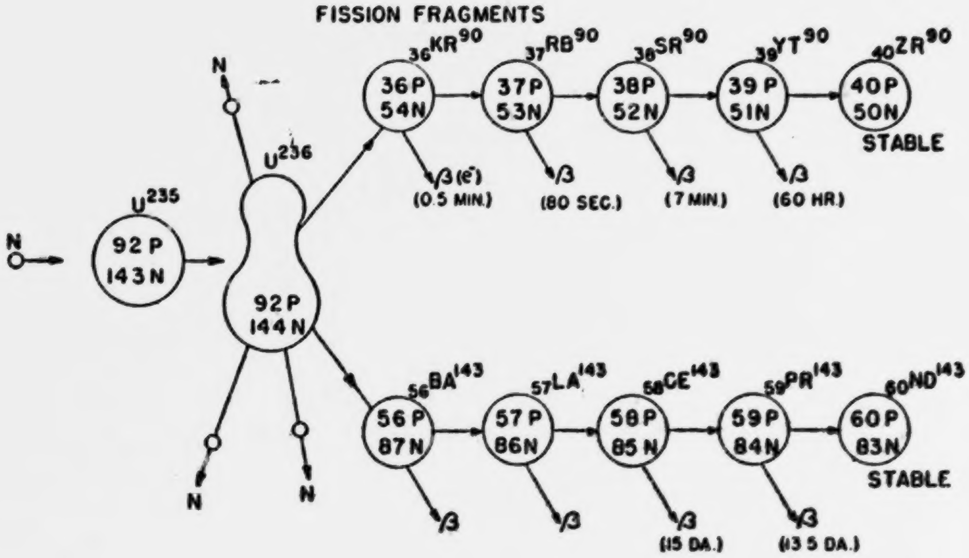

FISSION FRAGMENTS
N
U^{235}
92 P
143 N
U^{236}
92 P
144 N
N
N
N
$_{36}KR^{90}$
36 P
54 N
$\beta(e^-)$
(0.5 MIN.)
$_{37}RB^{90}$
37 P
53 N
β
(80 SEC.)
$_{38}SR^{90}$
38 P
52 N
β
(7 MIN.)
$_{39}YT^{90}$
39 P
51 N
β
(60 HR.)
$_{40}ZR^{90}$
40 P
50 N
STABLE
$_{56}BA^{143}$
56 P
87 N
β
$_{57}LA^{143}$
57 P
86 N
β
$_{58}CE^{143}$
58 P
85 N
β
(15 DA.)
$_{59}PR^{143}$
59 P
84 N
β
(13.5 DA.)
$_{60}ND^{143}$
60 P
83 N
STABLE

Fig. 16-2. Fission of uranium-235 and possible fission fragments (From Radioactivity and Nuclear Physics by J. M. Cork. 3d ed. Copyright 1957. D. Van Nostrand Company, Inc., Princeton, N. J. Used by permission.)

QUESTIONS

1. What is the major source of radioactive fallout?
2. What other sources of natural radioactive fallout have always existed?
3. Radioactive fallout from a nuclear detonation is transported by what means?
4. Would you expect more fallout at the onset of a rain than after rain has been falling for a period of time?
5. How can you explain the phenomenon that air samples collected on filters inside a building show almost the same radioactive contents as air samples obtained outside the building?
6. What are the three common nuclides that undergo fission?
7. What is the size of the standard sample of water used for checking radioactivity in rain water?
8. Which of the fission products is most damaging to animal life?
9. What type of rays are emitted by the radioactive particles found in fission products?
10. Describe the simple precautions that should be taken following exposure to rain containing a high level of radioactive fallout material.
11. Once fission products have been removed from a person's body, is there any danger of radiation to other people?

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17

tracer techniques

PLAN OF INSTRUCTION

OBJECTIVE

1. To introduce common tracer techniques used in plant and animal growth study.
2. To verify the absorption of inorganic substances (such as nitrogen, phosphorus, and potassium) from soil and to note how these are carried throughout the plant by translocation.
3. To introduce measurement techniques for tracer measurements.
4. To complete one tracer technique experiment on a live plant.

INTRODUCTION

1. Review measuring techniques for beta and gamma radiation.
2. Review self-absorption and absorption in matter for beta and gamma rays.
3. Review the corrections necessary to give an accurate count in the presence of absorption.
4. Review plant and animal growth and the assimilation of radioactive elements along with natural elements.

TEACHING PLAN

1. Plants assimilate food by their root systems and carry it up to the leaves through the inner layer of the stalk and stem.
2. Other plant products are carried down the outer section of the stalk to the root system.
3. The rate at which plant food is transported in a plant can be measured by "tagged atoms," minute quantities of radioactive matter. The movement of the compound can then be checked by measuring the radioactivity with a G-M tube.
4. Phosphorus-32 is a common element assimilated by both plants and animals.
5. Plant and animal foods can be made containing minute amounts of phosphorus-32.
6. Phosphorus-32 is a high energy beta emitter and suitable for use with G-M tubes but care must be taken that excessive absorption does not take place in the plant and animal tissues.
7. The movement of many types of food can be followed by the use of simple end-window G-M tube and a scaler.
8. Translocated radioactivity can be detected by the use of X-ray film and the autoradiograph techniques described in Session 16.

9. Carbon-14 can be incorporated into hydrocarbon compounds that can be used as food for animals.

10. Carbon-14 beta particles have low energy and great care must be used to avoid absorption in the animal tissue.

11. Iodine-131 is an excellent tracer element for locating certain animal glands, such as the thyroid.

12. Iodine-131 is both a beta and gamma radiator and is useful for treatment as well as detection.

13. Most elements are available as radioactive nuclides and almost any compound can be created for tracer work (See Appendix).

APPARATUS

G-M tube and rack to hold tube and sample

G-M scaler with variable voltage control.

Timing system, such as a timer or clock

Phosphorus-32, 10 μc

Growing plant: geranium, tomato, or celery

EXPERIMENTAL PROCEDURE

Vertical Translocation of Radioactive Phosphorus in a Plant

This experiment is designed to show that the movement of food material in a plant is upward on the inside section of the plant through a tissue known as the xylem and that plant matter produced in the leaves of the plant is transported downward on the very outside portion of the stem along a tissue called the phloem.

1. With a knife or scalpel, scrape a section of the stem of the geranium plant so that only the very outer tissues of the skin have been removed. The scraped area should be approximately half way up the plant and should be large enough so that a band-aid could cover the scraped area. Do not cut into the tissue and bare the xylem.

2. Soak a band-aid with 1 μc of phosphorus-32 and wrap the moist band-aid tightly around the scraped area of the plant.

3. Place a lead shield around the band-aid and radioactive phosphorus to shield the counter from the beta rays. At intervals of twenty minutes, test the area above and the area below the radioactive source for indication of motion of plant matter.

4. The phloem carries plant food from the leaves down to the roots and if the stalk was not scraped deep enough to bare the xylem, no translocation should appear upward.

5. On a second geranium plant, make a sufficiently deep incision so that a part of the xylem tissue is laid bare. This can be done by cutting away approximately 1/3 of the stem.

6. Apply a second band-aid impregnated with approximately 1 μc of phosphorus-32. Shield the radioactivity with a lead shield as before.

7. Make a series of measurements at intervals of about twenty minutes above and below the radioactive source.

8. Radioactivity should be noted above the incision and after some period of time the activity should extend all the way along the stems and into the leaves.

9. Since some of the active material made contact with the phloem because it was necessary to cut through the phloem to reach the xylem, a small amount of activity will be noted below the incision. (If a hypodermic needle is available, the radioactive phosphorus may be injected into the xylem tissue and thereby preventing contamination of the phloem by the radioactivity.)

Translocation of Phosphorus in Celery Stalks

The purpose of this experiment is to show that phosphorus-32 is translocated upward in a celery stalk.

1. Place several fresh celery stalks containing leaves in a jar containing 20 ml of water and 10 μc of phosphorus-32.

2. Allow the stalks to stand for twenty-four hours in an area that receives sunlight during the day.

3. Cut sections of the leaves and stalk and check each one for radioactivity.

4. Record the relative activity of the stalk in one-inch sections as a function of distance from the radioactive source.

5. Dry sections of the leaves and thin sections of the stalk under a sun-lamp.

6. Place the dried sections in contact with the emulsion side of an X-ray film after wrapping the film tightly in light paper, and leave the sections in contact with the film for one week.

7. Develop the X-ray film in X-ray developer and fixer and compare the intensity of the dissected sections with the relative activity readings obtained with the Geiger counter.

RESOURCE MATERIAL

Radioactive elements can be used for tracing the movement of plant matter and can provide useful information about such matters as the rate of growth and percent assimilation of plant foods. A small quantity of a radioactive element can be mixed with large quantities of natural elements to provide tagged atoms. Chemical bonds that hold atoms together in the form of molecules are a function of the electrons in the outer orbits of the atom. Since radioactivity is a function of the nucleus of the atom and since radioactive and nonradioactive atoms of the same element have identical electrons shells, radioactive elements enter into chemical combination with other atoms in exactly the same manner as those of the natural element.

Due to a phenomenon known as chemical equilibrium, atoms in a solution can be shown to enter into and leave combinations very readily. Thus, if a radioactive element is mixed with nonradioactive elements, there is a probability that the radioactive element will replace the natural element and in this new form the molecule will follow a normal path. For this reason, it is possible to expose the living tissue of a plant to a solution of a radioactive element that makes up part of a plant and have the radioactive element displace a similar element in the plant. Consequently, it is possible to follow the movement of this particular element throughout the plant.

Experiments with tagged atoms have made it possible for the scientist to observe the assimilation of plant foods containing, for instance, small amounts of phosphorus-32 and carbon-14 and to observe the rapidity with which the phenomenon of plant growth take place. When small amounts of phosphorus-32 are added to fertilizer and placed in the soil, the radioactive element can be detected in the plant within a few hours if a plant is watered and exposed to sun light. The action of sun light on the leaves produces the necessary reaction in the plant to cause the roots to absorb the fertilizer in solution form and to transport the plant food up the stems and to the leaves.

Many types of experiments illustrating this phenomenon can be devised but one of the simplest involves the flow of plant food downward in the phloem tissue to the roots and upward through the xylem tissue to the leaves.

In experiments of this type, it is generally sufficient to record the ratio of activity rather than to make absolute measurements of the activity, although it is possible to determine precisely the number of grams of a particular element that are transported by the plant system. Precise measurement is done by determining the total number of radioactive atoms in the original solution from a knowledge of the activity and to make a series of tests on various portions of the plant, taking care that all of the corrections for counting radioactive substances have been made.

It is similarly possible to determine the absorption of a particular element by animal tissue. In this case, radioactivity must be first introduced into a plant. When plant food is assimilated by the digestive system, the location of the tagged atoms and the time elapsed enables the scientist to determine the rate and location of the elements involved. Iodine-131 is used commonly to locate disorders in the thyroid, because the thyroid has a great affinity for iodine. Iodine-131 may be absorbed by the tissue by taking a sample orally, by injection into the flesh tissues, or by absorption through the skin. Not only is iodine-131 used to measure progress toward the thyroid. Since it is both beta and gamma active, it is used in large doses to irradiate the thyroid.

Both phosphorus and calcium are assimilated by the bones of animals and tagged atoms of radioactive phosphorus and calcium migrate toward the bones. A similarly interesting experiment is performed by placing 10 μc of phosphorus-32 in a goldfish bowl and allowing a goldfish to swim in the radioactive water for a week. If the flesh of the fish is removed, the fleshy tissue is found to have very little activity. Most of the radioactivity is found in the bone structure.

When time permits, autoradiographs can be made of bone structure or of sections of dried plant tissue by placing the samples on the emulsion side of an X-ray film. Radioactivity due to beta particles shows up as tiny darkened specks on the film and only general darkening occurs in the presence of gamma rays. The nuclide used in this experiment contains no alpha rays and, therefore, no characteristic alpha ray star-figures appear on the film.

Some estimate of the radioactivity produced by samples in the autoradiograph can be made by exposing the film to a number of calibrated radioactive samples. These samples are made by diluting a given quantity of radioactivity in water and moistening a filter paper with a series of known quantities of radioactivity. When an X-ray film is exposed to these calibrated samples, the darkening produced by this exposure can be compared with the darkening produced by an experimental sample.

QUESTIONS

1. What is meant by the use of radioactivity for tracer purposes?
2. How are the tracer elements produced?
3. In plant and animal life, is it necessary that the tagged atoms be absorbed by the tissue?
4. Are elements that emit alpha rays generally used for tracers?
5. What type of ray is most effective for use in tracer techniques?
6. Radioactive tracer techniques are used in transmission of oil by pipelines when a change in the type of oil is made. Suggest a method that could be used to indicate the start of a new type of oil.

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18

cloud chambers

PLAN OF INSTRUCTION

OBJECTIVE

1. To view alpha and beta particles in a cloud chamber.
2. To visually observe the intensity of ionization produced by alpha particles as compared with the ionization produced by beta particles.
3. To visually observe the deflection of positively and negatively charged particles by a magnetic field.
4. To study the need for a clearing field to sweep spent ions out of the viewing area.

INTRODUCTION

1. Review the ionization capabilities of beta particles and alpha particles.
2. Review the intensity of ionization of beta particles and alpha particles.
3. Review the behavior of positive and negative ions in an electric field and the Coulomb forces acting on the ions.
4. Review the mobility of positively charged ions and electrons produced by radioactive rays.

TEACHING PLAN

1. A volume of clean air supersaturated with water vapor and alcohol is sensitive to the formation of water droplets known as fog.
2. The conditions of supersaturation can be produced continually by creating a diffusion layer of air warm at the top and very cold at the bottom of a chamber.
3. A supersaturated condition can also be produced by suddenly expanding the volume of air in a chamber, producing cooling by expansion and thereby reducing the temperature to below the dew-point.
4. Fog droplets cannot form without an initial nucleus of some impurity such as dust, smog, or an ion.
5. Fog particles will form around a positive ion or a negative ion.
6. Positive ions are produced by the removal of one electron from an atom of oxygen or nitrogen.
7. The free electron associates itself almost immediately with a nitrogen or oxygen atom forming a negative ion.
8. Air supersaturated with water vapor causes billions of water molecules to immediately form around the ion.

9. The water droplets can be observed visually or can be recorded by photographic methods.

10. The alpha and beta rays producing the ionization obey the usual formulas for curvature in a magnetic field and the resulting path as observed by the water droplets that form on the ions will indicate the path taken by the radioactive particle.

APPARATUS

Atomic Laboratories, Inc., Raymaster Cloud Chamber
Slab of dry ice, one inch thick, seven inches square
200 ml methyl alcohol

or

Cenco-Knipp Alpha Ray Track Apparatus

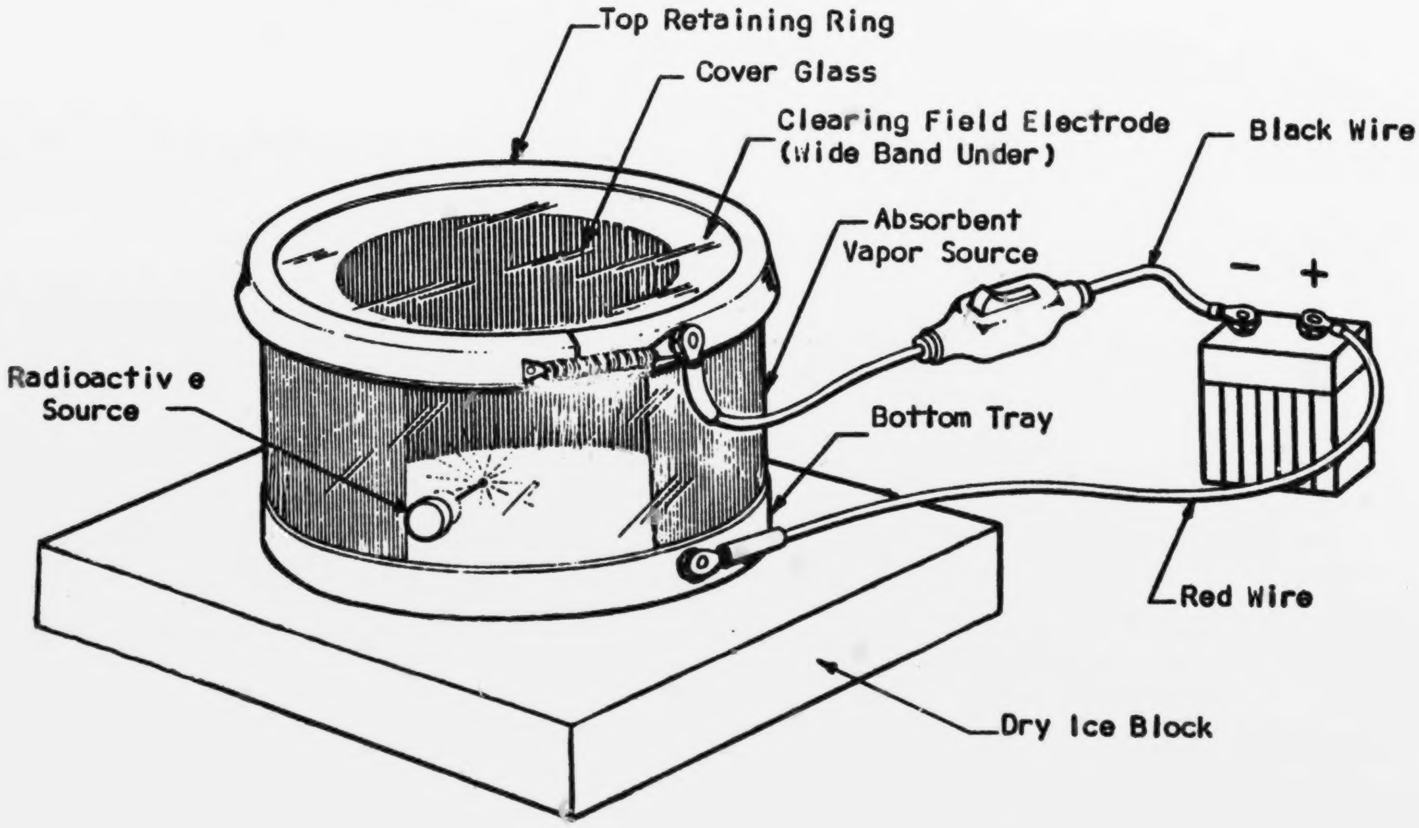

Top Retaining Ring
Cover Glass
Clearing Field Electrode (Wide Band Under)
Black Wire
Absorbent Vapor Source
− +
Radioactive Source
Bottom Tray
Red Wire
Dry Ice Block

Fig. 18-1. Raymaster cloud chamber assembly (From Laboratory Manual, Raymaster Cloud Chamber. Atomic Laboratories, Inc., San Ramon, Calif. Used by permission.)

EXPERIMENTAL PROCEDURE

Raymaster Cloud Chamber

1. Assemble the equipment as shown in Fig. 18-1. (Dry ice can be purchased in many creameries, or look under "Dry Ice" in the yellow pages of the telephone directory.)

2. Fill the bottom of the Raymaster with methyl alcohol to a depth of 1/8 inch. Add 1/2 teaspoon of black dye and stir until dissolved. Washable black ink may be used. A black background is necessary for satisfactory viewing of fog tracks.

3. The alcohol will rise up the black blotting paper by capillary attraction. Sufficient alcohol must be used so that the black blotter is completely saturated but not so much that the alcohol acts as a heat insulator.

4. Place the glass cover and the retaining ring on top of the apparatus.

5. Connect the clearing field. The apparatus is ready to operate in about five minutes.

6. Radioactive sources furnished with the Raymaster are alpha and beta sources in the form of beads on the heads of needles. The needles are imbedded in rubber stoppers.

7. Insert the desired source into the hole in the side of the cloud chamber and push the rubber stopper tightly to prevent air leaks.

8. The alpha source contains a minute amount of radium and the beta source contains strontium-90. Both are absolutely safe to handle if the radioactive beads are not touched.

9. Adjust the light source used with the cloud chamber so that the interior of the chamber is brightly illuminated.

10. The clearing field may be left on or momentarily turned off and tracks should be visible in the chamber.

11. Compare the length of the tracks due to alpha particles with the range for radium-226 given in the Appendix.

12. Bring an alnico V magnet near the source and note the deflection of the rays produced by the magnetic field.

13. Approximately 4×10^4 ion pairs are produced per centimeter length by alpha particles. For this reason, it may be difficult to count the ion pairs.

14. Insert the beta source and determine the direction of deflection and the intensity of ionization as observed by the droplets formed on the ion track.

15. The alpha source furnished with this cloud chamber consists of radium-226 with a range of 3.3 cm and a half-life of 1,620 years.

Cenco-Knipp Apparatus

This experiment is based on the Wilson cloud chamber.

1. Plug the A-C cord into a standard socket and a powerful light will illuminate the area above the water in the cloud chamber.

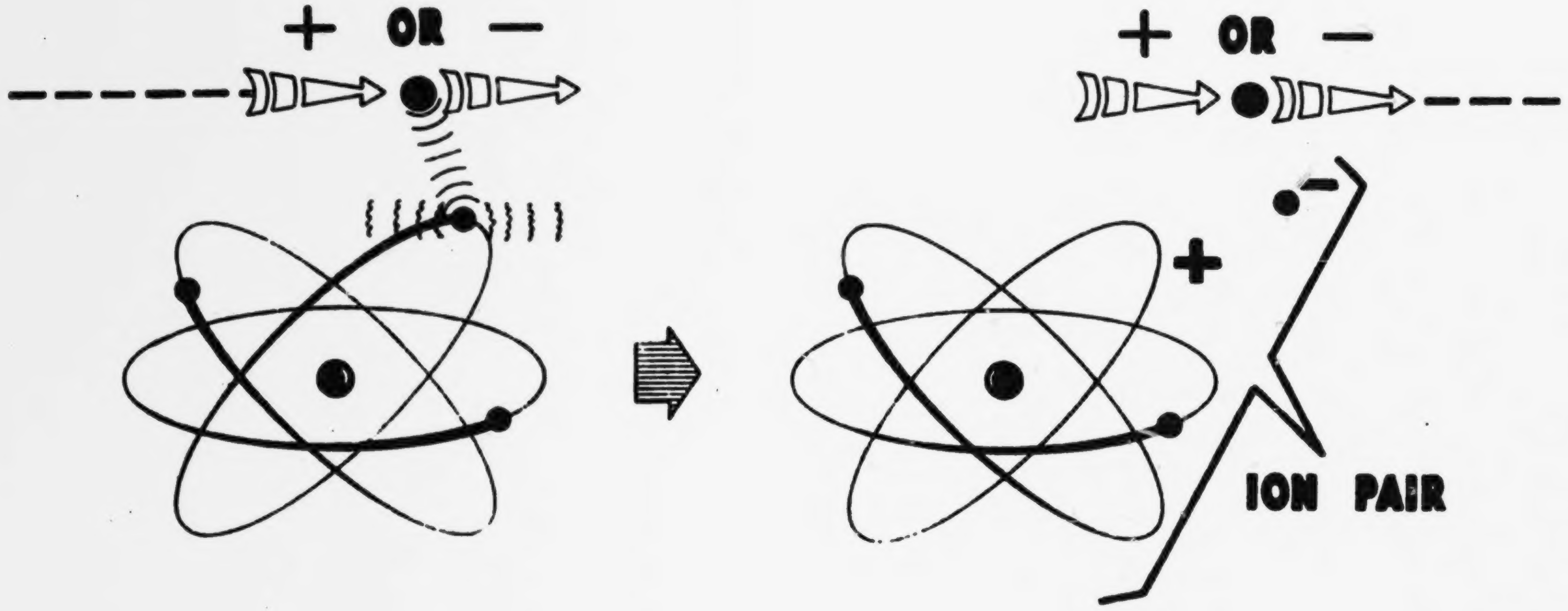
2. Attach a 45-volt clearing battery to the terminals provided for this purpose. (Note: The clearing battery does not need to be disconnected and a switch is not necessary to turn the voltage on or off.)

3. The alpha particles are produced by a small amount of radium-226 attached to a point imbedded in the chamber.

4. Squeeze the bulb and hold for approximately ten seconds and suddenly release the bulb. The track should be visible for approximately five seconds immediately after releasing the bulb.

5. The clearing field will sweep the spent ions away rapidly, and the bulb may be depressed again for a second view.

IONIZATION BY CHARGED PARTICLE



ELECTRON IS GIVEN SUFFICIENT ENERGY TO EJECT IT

IONS THEN:
- REACT CHEMICALLY WITH MATTER
- MOVE IN ELECTRIC FIELDS
- RECOMBINE — EMITTING LIGHT
- SERVE AS CONDENSATION NUCLEI

USAEC-ID-191A

6. If desired, a camera arrangement may be used to record the tracks produced in this experiment.

7. Bring the alnico V magnet near the radioactive source and observe the deflection with the magnet in place. (Caution: Part of the stand is made of iron and will be attracted violently if the magnet is brought close to the iron. Great care should be exercised to avoid damaging the equipment.)

8. Faint tracks are occasionally observed in the cloud chamber. These are due to beta particles from impurities or cosmic rays from the outer atmosphere.

RESOURCE MATERIAL

C. T. R. Wilson developed the basic methods used for research on radioactive samples and other high-energy particles in the development of the cloud chamber. The cloud chamber consists of a volume of air supersaturated with water, alcohol, or a combination of the two.

Two separate types of equipment are now available: the continuous cloud chamber, consisting of an unstable section of air that is warm in its upper region and cold in its lower region; and a system wherein the instability is artificially produced by suddenly cooling the air by expansion. In either type, however, water droplets cannot form without nuclei of some sort. Dust particles in the atmosphere form the nuclei for condensation; this is one of the sources of smog. In the absence of such nuclei, silver iodide is commercially used to induce rain, for example, by providing the small nuclei about which fog droplets and ultimate rain drops form.

In the cloud chamber used for scientific purposes, air is thoroughly cleaned. Under these circumstances, the region becomes supersaturated but fog droplets cannot form without nuclei. If an ionizing ray produces ions in the air, these ions serve as nuclei for the formation of droplets. Since a ray passing through the region produces positive and negative ions, as many fog droplets are formed as there are ions along the ray path. Approximately 4 x 10^4 ion pairs are produced by alpha particles and these are along an extremely narrow path. If such a series of water droplets is illuminated by a bright light and observed against a dark background, a fine white line marks the path taken by the ions. The intensity of the line is proportional to the ionization produced and may be used to identify the type of ray.

It is actually possible to count the ion pairs by photographing an ionizing ray a short time after the ionization has been produced. The ions will have separated by diffusion and a fairly accurate determination of the number of ion pairs per centimeter length can be made by the use of photographic techniques and a microscope.

Fog particles produced in a cloud chamber are the result of supercooling saturated air. The number of particles per centimeter length is determined by the density of the air in terms of mg/cm^3. The same technique is now applied to the production of tracks by utilizing a similar phase in liquids. If a liquid is superheated, that is, heated to beyond the normal boiling point of the liquid, active turbulence and bubble formation will not take place if the liquid contains no foreign particles. Special techniques are employed to assure that no impurities are added to the liquid by the walls of the chamber. Under these conditions it is possible to raise the temperature of the liquid into the superheated region. Such an arrangement is known as a bubble chamber.

When an ionizing ray enters the liquid in the bubble chamber, microscopically small bubbles form on the ions produced by the ionizing ray. These bubbles grow and become large enough to reflect light and become visible. Inasmuch as the density of the liquid is very much larger than air, approximately 1,000 mg/cm^3 for liquids as compared to 1.23 mg/cm^3 for air, the amount of ionization produced is increased by a factor of 1,000 and the probability of observing a nuclear reaction is increased by the same factor. Since Wilson cloud chambers have a practical maximum size of approximately one foot, a bubble chamber having a diameter of one foot is equivalent to a Wilson cloud chamber having a dimension of one-fourth mile.

Many liquids can be used for bubble chambers, including benzene, carbon tetrachloride, and hydrogen. A most popular liquid is the hydrogen, which is operated at temperatures near the boiling point, or -253°C. Obviously, special techniques must be employed in order to operate such a bubble chamber. Bubble chambers of this type are used with rays having energies up to and above 10 Bev (billion electron volts) in advanced types of research.

QUESTIONS

1. What conditions are required to form visible drops of moisture in saturated air?
2. Will moisture form in unsaturated air?
3. What is the purpose for the bright light in the cloud chamber experiment?
4. A dark background made by the use of black velvet or water blackened with ink is often used in cloud chamber experiments. What is the purpose of the black background?
5. How do you distinguish between alpha and beta rays in a cloud chamber?
6. Why is it nearly impossible to detect gamma rays in a cloud chamber?
7. Describe the action of the clearing field.
8. Describe what happens when the clearing field is left on continuously.
9. Can you suggest a reason why radioactive contaminates in the form of dust particles inside a cloud chamber are not normally satisfactory for observing rays?
10. Discuss the similarity of the bubble chamber with that of the cloud chamber.
11. What is the advantage of the bubble chamber over the cloud chamber for observing radioactive phenomena?

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appendix

Table A
INTERNATIONAL ATOMIC WEIGHTS

Element	*Symbol*	*number*	*weight*
Actinium	Ac	89	227
Aluminum	Al	13	26.98
Americium	Am	95	(243)
Antimony	Sb	51	121.76
Argon	A	18	39.944
Arsenic	As	33	74.91
Astatine	At	85	(210)
Barium	Ba	56	137.36
Berkelium	Bk	97	(245)
Beryllium	Be	4	9.013
Bismuth	Bi	83	209.00
Boron	B	5	10.82
Bromine	Br	35	79.916
Cadmium	Cd	48	112.41
Calcium	Ca	20	40.08
Californium	Cf	98	(246)
Carbon	C	6	12.010
Cerium	Ce	58	140.13
Cesium	Cs	55	132.91
Chlorine	Cl	17	35.457
Chromium	Cr	24	52.01
Cobalt	Co	27	58.94
Copper	Cu	29	63.54
Curium	Cm	96	(243)
Dysprosium	Dy	66	162.46
Erbium	Er	68	167.2
Europium	Eu	63	152.0
Fluorine	F	9	19.00
Francium	Fr	87	(223)
Gadolinium	Gd	64	156.9
Gallium	Ga	31	69.72
Germanium	Ge	32	72.60
Gold	Au	79	197.2
Hafnium	Hf	72	178.6
Helium	He	2	4.003
Holmium	Ho	67	164.94
Hydrogen	H	1	1.0080
Indium	In	49	114.76
Iodine	I	53	126.91
Iridium	Ir	77	193.1
Iron	Fe	26	55.85
Krypton	Kr	36	83.80
Lanthanum	La	57	138.92
Lead	Pb	82	207.21
Lithium	Li	3	6.940
Lutetium	Lu	71	174.99
Magnesium	Mg	12	24.32
Manganese	Mn	25	54.93
Mercury	Hg	80	200.61
Molybdenum	Mo	42	95.95
Neodymium	Nd	60	144.27
Neon	Ne	10	20.183
Neptunium	Np	93	(237)
Nickel	Ni	28	58.69
Niobium (Columbium)	Nb	41	92.91
Nitrogen	N	7	14.008
Osmium	Os	76	190.2
Oxygen	O	8	16.000
Palladium	Pd	46	106.7
Phosphorus	P	15	30.975
Platinum	Pt	78	195.23
Plutonium	Pu	94	(242)
Polonium	Po	84	210
Potassium	K	19	39.100
Praseodymium	Pr	59	140.92
Promethium	Pm	61	(145)
Protactinium	Pa	91	231
Radium	Ra	88	226.05
Radon	Rn	86	222
Rhenium	Re	75	186.31
Rhodium	Rh	45	102.91
Rubidium	Rb	37	85.48
Ruthenium	Ru	44	101.7
Samarium	Sm	62	150.43
Scandium	Sc	21	44.96
Selenium	Se	34	78.96
Silicon	Si	14	28.09
Silver	Ag	47	107.880
Sodium	Na	11	22.997
Strontium	Sr	38	87.63
Sulfur	S	16	32.066
Tantalum	Ta	73	180.88
Technetium	Tc	43	(99)
Tellurium	Te	52	127.61
Terbium	Tb	65	159.2
Thallium	Tl	81	204.39
Thorium	Th	90	232.12
Thulium	Tm	69	169.4
Tin	Sn	50	118.70
Titanium	Ti	22	47.90
Tungsten	W	74	183.92
Uranium	U	92	238.07
Vanadium	V	23	50.95
Xenon	Xe	54	131.3
Ytterbium	Yb	70	173.04
Yttrium	Y	39	88.92
Zinc	Zn	30	65.38
Zirconium	Zr	40	91.22

(From Nuclear Radiation Physics by R. E. Lapp and H. L. Andrews. 3d ed. Copyright 1963. Prentice-Hall, Inc., Englewood Cliffs, N. J. Used by permission.)

Table B
A LIST OF USEFUL RADIOACTIVE ISOTOPES

Element	Nucleus	Half life	Beta particle (Mev)	Gamma ray (Mev)
Aluminum	Al^{29}	6.56 min	2.5, 1.4	1.2, 2.3
Antimony	Sb^{122}	2.8 days	1.36, 1.94	0.568
	Sb^{124}	60 days	0.5→2.37	0.121→2.3 (10γ)
	Sb^{125}	2.7 yr	0.128, 0.299, 0.616	0.035→0.637 (7γ)
Argon	A^{37}	34.1 days	K	None
	A^{41}	1.78 min	1.25	1.3
Arsenic	As^{76}	26.8 hr	0.4, 1.4, 2.56, 3.12	0.57, 1.25, 1.8, 2.1
	As^{77}	40 hr	0.7	None
Astatine	At^{211}	7.5 hr	5.89α, K	—
Barium	Ba^{131}	12 days	K	0.122 → 0.494
	Ba^{140}	12.8 days	0.48, 1.022	0.160, 0.306, 0.540
Beryllium	Be^{7}	54.5 days	K	0.478
	Be^{10}	2.5×10^{6} yr	0.555	None
Bismuth	Bi^{210}	4.85 days	1.17	None
Bromine	Br^{82}	35.1 hr	0.465	0.547, 0.787, 1.35, 1.7-2.0
Cadmium	Cd^{115}	2.3 days,	0.58, 1.11,	0.34, 0.5, 0.52
	Cd^{115}	43 days	0.7, 1.61	0.46, 0.50, 0.96, 1.28
Calcium	Ca^{45}	152 days	0.255	None
Carbon	C^{11}	20.35 min	$0.970e^{+}$	—
	C^{14}	5,720 yr	0.155	None
Cerium	Ce^{141}	33.1 days	0.442, 0.581	0.141,
Cesium	Cs^{134}	2.3 yr	0.658, 0.090, 0.24	0.568, 0.602, 0.794, 1.36
Chlorine	Cl^{36}	4.4×10^{5} yr	0.713	Weak (0.10)
	Cl^{38}	37.3 min	1.11, 2.77, 4.81	1.60, 2.15
Chromium	Cr^{51}	26.5 days	K	0.320, 0.267
Cobalt	Co^{56}	80 days	$1.50e^{+}$	0.85, 1.3, 2.6, 3.3
	Co^{60}	5.26 yr	0.31	1.17, 1.33
Copper	Cu^{64}	12.8 hr	$0.58e^{-}$, $0.66e^{+}$	1.34
Europium	Eu^{154}	5.4 yr	0.3, 0.7, 1.9	~1.2
	Eu^{155}	1.7 yr	0.154→1.88	0.084→1.288
Fluorine	F^{18}	1.87 hr	$0.64e^{+}$	—
Gallium	Ga^{66}	9.2 hr	$3 9e^{+}$	—
	Ga^{72}	14 1 hr	0.64, 0 96, 1.48	0.63→2.50
Germanium	Ge^{71}	11.4 days	K	None
	Ge^{77}	12 hr	1.74	0.5
Gold	Au^{198}	2.69 days	0.98	0.411
	Au^{199}	3.3 days	0.32	0.24→0.23 (6γ)
Hafnium	Hf^{181}	45 days	0.405	0.133→0.612
Hydrogen	H^{3}	12.5 yr	0.0189	None
Indium	In^{114}	50 days	IT $0.60e^{+}$, 2.05	0.192, 0.548, 0.715, 1.27
Iodine	I^{131}	8.0 days	0.315, 0.600	0.367, 0.080, 0.284, 0.638
Iridium	Ir^{192}	74.7 days	0.67	0.137→0.651 (12γ)
	Ir^{194}	19 hr	0.48, 2.18	0.38, 1.43
Iron	Fe^{55}	2.91 yr	K	None
	Fe^{59}	46.3 days	0.26, 0.46	1.1, 1.3
Krypton	Kr^{85}	4.5 hr	1.0	0.17, 0.37
Lanthanum	La^{140}	40 hr	1.32, 1.67, 2.26	0.093→2.5
Magnesium	Mg^{27}	9.58 min	0.9, 1.80	0.64, 0.84, 1.02
Manganese	Mn^{52}	6.0 days	$2.66e^{+}$, K	0.734, 0.94, 1.46
	Mn^{54}	310 days	K	0.835
Mercury	Hg^{197}	65 hr	K	0.075
		25 hr	K	0.135, 0.165, 0.273
	Hg^{203}	43.5 days	0.205	0.286

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Table B
A LIST OF USEFUL RADIOACTIVE ISOTOPES

Element	Nucleus	Half life	Beta particle (Mev)	Gamma ray (Mev)
Molybdenum	Mo^{99}	68.3 hr	0.445, 1.23	0.04, 0.741, 0.780
Neodymium	Nd^{147}	11 days	0.17, 0.78	0.035, 0.58
Nickel	Ni^{63}	85 yr	0.063	None
Niobum	Nb^{95}	90 hr, 35 days	IT 0.163	0.771
Nitrogen	N^{13}	10.1 min	$1.23e^+$	None
Osmium	Os^{185}	97 days	*K*	0.648, 0.878
	Os^{191}	15.0 days	0.142	0.039, 0.127
	Os^{193}	32 hr	1.15	1.58
Oxygen	O^{15}	1.97 min	$1.683e^+$	—
Palladium	Pd^{103}	17 days	*K*	None
Phosphorus	P^{32}	14.3 days	1.718	None
Platinum	Pt^{197}	18 hr	0.65	None
Polonium	Po^{210}	138.3 days	5.298	0.773
Potassium	K^{40}	9.9×10^8 yr	1.40	1.45, *K*
Fraeseodymium	Pr^{142}	19.1 hr	0.636, 2.154	1.57
	Pr^{143}	13.8 days	0.932	None
Promethium	Pm^{147}	2.26 yr	0.229	None
Rhenium	Re^{186}	92.8 hr	0.64, 0.95, 1.09	0.132, 0.275, 1.70
	Re^{188}	18.9 hr	2.10	$0.15 \rightarrow 1.39\ (5\gamma)$
Rhodium	Rh^{105}	36.2 hr	0.57	0.33
Rubidium	Rb^{86}	19.5 days	0.72, 1.80	1.08
Ruthenium	Ru^{97}	2.8 days	*K*	0.23
	Ru^{103}	42 days	0.205, 0.670	0.494
	Ru^{106}	1.0 yr	0.041	None
Samarium	Sm^{153}	47 hr	0.68, 0.80	0.070, 0.103, 0.61
Scandium	Sc^{46}	85 days	0.36, 1.49	0.89, 1.12
	Sc^{48}	1.83 days	0.64	0.98, 1.33
Selenium	Se^{75}	128 days	*K*	$0.076 \rightarrow 0.405$
Silicon	Si^{31}	2.59 hr	1.5	None
Silver	Ag^{110}	270 days	0.087, 0.53	0.885, 0.935, 0.1389, 1.516
	Ag^{111}	7.5 days	1.06	None
Sodium	Na^{22}	2.6 yr	$0.58e^+$	1.3
	Na^{24}	15.0 hr	1.390	1.380, 2.758
Strontium	Sr^{89}	53 days	1.50	None
	Sr^{90}	19.9 yr	0.54	None
Sulfur	S^{35}	87.1 days	0.167	None
Tantalum	Ta^{182}	115 days	0.52, 1.1	$0.05 \rightarrow 1.24\ (33\gamma)$
Technetium	Tc^{97}	90 days, $> 10^3$ yr	IT	0.097
	Tc^{99}	2.1×10^5 yr	0.30	0.140
Tellurium	Te^{127}	90 days, 9.3	IT ~0.8	0.089
	Te^{129}	32 days, 72 min	IT ' 75	0.102, 0.3, 0.8
	Te^{131}	30 hr, 25 min	IT >1.8	0.177
Thallium	Tl^{204}	2.7 yr	0.783	None
Tin	Sn^{113}	112 days	*K*	0.085
Tungsten	W^{185}	73.2 days	0.428	None
	W^{187}	24.1 hr	0.627, 1.318	$0.086 \rightarrow 0.70$
Vanadium	V^{48}	16 days	$0.716e^+$, *K*	0.990, 1.320
Xenon	Xe^{131}	12.0 days	IT	0.163
Yttrium	Y^{90}	61 hr	2.24	None
Zinc	Zn^{65}	250 days	0.32, *K*	1.11
	Zn^{69}	13.8 hr	0.86	IT 0.44
Zirconium	Zr^{95}	65 days	0.400, 0.887	0.216, 0.708, 0.92
	Zr^{97}	17.0 hr	2.2	0.8

Table C
PHYSICAL CONSTANTS AND USEFUL DATA

Symbol	*Quantity*	*Value*
c	Velocity of light	2.99793×10^{10} cm/sec
h	Plank's constant	6.6252×10^{-27} erg-sec
k	Boltzmann's constant	1.38042×10^{-16} erg/deg 8.6164×10^{-5} ev/deg
F	The Faraday constant	9652.0 emu/mole (physical) 2.8936×10^{14} esu/mole
R_∞	The Rydberg constant	109,737.30 cm^{-1}
N	Avogadro's number	6.0247×10^{23} mole^{-1}
R	Universal gas constant	8.31662×10^{7} erg/deg/mole
e	Electronic charge	4.8028×10^{-10} esu 1.6020×10^{-19} coulomb
e/m	Electron charge-to-mass ratio	1.7588×10^{7} emu/gram 5.2730×10^{17} esu/gram
V_0	Volume of 1 mole of ideal gas	22,420.7 cm^3 (NTP)
$\lambda_{max} T$	Wein Displacement law constant	0.28979 cm/deg
σ	Stefan-Boltzmann constan	0.56686×10^{-14} $\text{erg/cm}^{-1}/\text{deg}^{-4}/\text{sec}^{-1}$
μ_0	Bohr magneton	0.92732×10^{-20} erg/gauss
μ_e	Magnetic moment of electron	0.92838×10^{-20} erg/gauss
μ_m	Nuclear magneton	0.50504×10^{-23} erg/gauss
μ	Proton moment	2.79277 nuclear magnetons
m_e	Electron = 0.51098 Mev	= 9.1085×10^{-28} gram = 0.000549 amu*
m_n	Neutron = 939.526 Mev	= 1.67474×10^{-24} gram = 1.008982 amu
m_p	Proton = 938.232 Mev	= 1.67243×10^{-24} gram = 1.007593 amu
m_H	H^1 atom = 938.743 Mev	= 1.67334×10^{-24} gram = 1.008142 amu

1 kg = 2.205 lb
1 liter = 0.879 qt
1 km = 0.6214 miles
1 cm = 0.3037 in.
1 Angstrom = 10^{-8} cm
1 watt = 1 joule/sec
1 hp = 746 watts
1 Btu = 1.055×10^{10} ergs
1 amp = $6.244 \times 10^{18} e$/sec

1 lb = 453.6 grams
1 qt = 1.137 liters
1 in. = 2.540 cm
1 cu m = 35.31 cu ft
1 micron = 10^{-6} m
1 joule = 10^{7} ergs
1 Btu = 252 calories
1 kw-hr = 3413 Btu
1 gram = 5.6099×10^{26} Mev
1 ev = 1.60207×10^{-12} erg

1 roentgen = 1 esu/cc standard air
= 2.083×10^{9} ion pairs/cc standard air
1 roentgen = 83.8 ergs/gram of air
= 1.61×10^{12} ion pairs/gram of air
1 roentgen = 6.77×10^{4} Mev/cc standard air
= 5.24×10^{7} Mev/gram of air
1 hour = 60 min = 3600 sec
1 day = 1440 min = 8.64×10^{4} sec
1 year = 5.26×10^{5} min = 3.15×10^{7} sec

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Table D
CONVERSION TABLE

Multiply	*By*	*To obtain*
Atomic mass units	9.31×10^{2}	Mev
	1.49×10^{-3}	ergs
	3.56×10^{-11}	calories
	4.15×10^{-17}	kilowatt-hours
Mev	1.07×10^{-3}	atomic mass units
	1.60×10^{-6}	ergs
	3.83×10^{-14}	calories
	4.45×10^{-20}	kilowatt-hours
Ergs	6.71×10^{2}	atomic mass units
	6.24×10^{5}	Mev
	2.39×10^{-8}	calories
	2.78×10^{-14}	kilowatt-hours
Calories	2.81×10^{10}	atomic mass units
	2.62×10^{13}	Mev
	4.18×10^{7}	ergs
	1.16×10^{-6}	kilowatt-hours
Kilowatt-hours	2.41×10^{16}	atomic mass units
	2.25×10^{19}	Mev
	3.60×10^{13}	ergs
	8.60×10^{5}	calories

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the greek alphabet

Α	α	Alpha	Η	η	Eta	Ν	ν	Nu	Τ	τ	Tau
Β	β	Beta	Θ	θ	Theta	Ξ	ξ	Xi	Τ	υ	Upsilon
Γ	γ	Gamma	Ι	ι	Iota	Ο	ο	Omicron	Φ	φ	Phi
Δ	δ	Delta	Κ	κ	Kappa	Π	π	Pi	Χ	χ	Chi
Ε	ε	Epsilon,	Λ	λ	Lambda	Ρ	ρ	Rho	Ψ	ψ	Psi
Ζ	ζ	Zeta	Μ	μ	Mu	Σ	σ	Sigma	Ω	ω	Omega

fundamentals of nuclear radiations

Atom: Basic chemical unit of matter:

nucleus | protons--positive charge.
nucleus | neutrons--neutral charge.

electrons--negative charge, $\frac{1}{1,840}$ weight of proton or neutron.

nucleus--10^{-13} cm. diameter; atom 10^{-8} cm.

Number protons = number electrons in intact atoms.

Chemical reactions occur by interactions between electron shells, nuclear reactions by transformations within atomic nuclei.

Element--Matter composed of a single kind of atom.

Atomic number--sum of protons in a nucleus.

Atomic weight--sum of protons + neutrons in a nucleus.

Isotopes--Different forms of same element, differing by number of neutrons in the nucleus.

Nuclear radiation--That emitted when changes occur within atomic nucleus. Biologically harmful. Cannot be detected by human senses.

Radioactivity--Phenomenon associated with the emanation of nuclear radiation.

Radioactive substance--One which emits nuclear radiations.

Radioactive decay--Process which unstable (radioactive) nuclei undergo in achieving stability. This is represented by an observed decrease in radiation with time (from a given source).

Half-life--time required for a quantity of a radioactive substance to lose half its activity; i.e., time required for half its atoms to decay. Constant for a given radioisotope.

Isotopes--1. Stable.
- 2. Unstable.
  - a. Naturally occurring.
  - b. Artificially produced (induced).

Induced radioactivity--Except in particle accelerators (cyclotrons, etc.), radioactivity is induced in stable atoms only by neutrons. Exposure of materials to other types of radiation will not cause the materials to be made radioactive.

Fission--Neutron induced splitting of a large atomic nucleus into two smaller ones. Some mass is converted to energy in the process. Products are highly radioactive. This is the basic reaction in explosion of atomic bombs, also the one causing atomic piles and nuclear reactors to operate.

Fusion or thermonuclear reaction--Coalescence of two small atoms to form a large one. Some mass is converted to energy in the process. Basis of the "hydrogen" bomb, as well as source of energy of the sun. Extremely high temperatures required to activate.

Curie (c)--An amount of radioactive material that undergoes 3.7×10^{10} disintegrations per second. A measure of the strength of a radioactive source.

1 curie = 1,000 millicuries (mc) ≐ 1,000,000 microcuries (μc)

Roentgen (r)--Quantity or dose of radiation. Exact definition based on ionization produced in air by X or gamma radiation.

1 roentgen = 1,000 milliroentgens (mr)

Roentgen equivalent physical (rep) | Units devised to extend roentgen to include all types
Roentgen equivalent man (rem) | of radiations and their damage to body tissue.

There is no simple relation between curies and roentgens. A different conversion factor is necessary for each isotope.

Dose = rate x time (for materials with half-lives long in relation to exposure time).
Rate in r/hr or mr/hr (speedometer, rate meter).
Dose in r or mr (mileage indicator, integrating instrument).

Inverse square law--Intensity of radiation from a point source decreases with the square of the distance from the source.

$$\frac{I_1}{I_2} = \left(\frac{d_2}{d_1}\right)^2$$

units: conversions and definitions

Curie (c): Amount of radioactive material that undergoes 3.7×10^{10} disintegrations per second (d/s or dps).

3.7×10^{10} = 37 billion = 37,000,000,000

Millicurie (mc): $\frac{1}{1,000}$ of a curie = 3.7×10^{7} dps.

Microcurie (μc): $\frac{1}{1,000,000}$ of a curie = 3.7×10^{4} dps.

Roentgen (r): Quantity or dose of radiation. Exact definition based on amount of ionization produced.

Roentgen equivalent physical (rep)
Roentgen equivalent man (rem)
| Units devised to extend roentgen to include all types of nuclear radiation, and to signify the amount of ionization and damage caused in biological systems

Milliroentgen (mr): $\frac{1}{1,000}$ of a roentgen.

Total: Mileage indicator--dosimeter, film badge.
Rate: Speedometer--portable survey instruments.

Dose = rate x time (for materials with long half-lives).

Rate in r/hr or mr/hr; dose in r or mr; time in hours.
1 mgm. Radium = 1 millicurie = 8.4 r/hr at 1 cm.

Inverse square law--Intensity of radiation from a point source decreases with the square of the distance from the source.

For radium:

$$\text{r/hr} = \frac{1.3 \times \text{milligrams of radium (mc)}}{(\text{distance in inches})^2}$$

$$\text{Distance in inches from source for a given reading} = \sqrt{\frac{1.3 \times \text{mgm Ra (mc)}}{\text{r/hr you want}}}$$

For Co^{60}:

$$\text{r/hr} = \frac{2.1 \times \text{activity in millicuries}}{(\text{distance in inches})^2}$$

$$\text{Distance in inches from source for a given reading} = \sqrt{\frac{2.1 \times \text{activity in mc}}{\text{r/hr you want}}}$$

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APPENDIX

ILLUSTRATIONS

The following illustrations are available from the Office of Isotope Development, United States Atomic Energy Commission, Washington, D. C.:

- Isotope Applications in Physical Sciences
- Isotope Production and Availability
- Isotope Characteristics
- Definitions of Radioisotopes
- Isotope Applications in Biology and Medicine, Research
- Isotope Applications in Biology and Medicine, Therapy
- Isotope Applications in Industry
- Isotope Applications
- Isotope Applications in Agriculture

FILMS

Professional Level Film List

The following films are available free from Commanding General, Sixth Army, Presidio of San Francisco, California, Attention: Central Film Exchange:

SESSION NO. 1 - Fundamentals of Radioactivity (PMF 5145-A), 59 minutes
SESSION NO. 4 - Principles of Radiological Safety (PMF 5145-E), 51 minutes
SESSION NO. 5 - Practical Procedures of Measurement (PMF 5145-C), 48 minutes
SESSION NO. 7 - Properties of Radiation (PMF 5145-B), 68 minutes
SESSION NO. 17 - Radioisotopes in Agricultural Research (PMF 5147-B), 40 minutes

Educational Motion Pictures

The following films are available from the University of California, Public Film Rental Library. Fees vary from film to film.

SESSION NO. 1 - Explaining Matter: Atoms & Molecules, No. 4835, 13 minutes
SESSION NO. 3 - How Big Are Atoms, No. 5426, 30 minutes
SESSION NO. 16 - Principles of Nuclear Fission, No. 5455, 10 minutes
SESSION NO. 17 - Tagging the Atom, No. 4520, 12 minutes

RESOURCE MATERIALS

Cross-referenced Index of Radiochemical Teaching Experiments Applicable to Chemistry. National Academy of Sciences--National Research Council.

McCormick, J. A. Isotopes in Biochemistry and Biosynthesis of Labeled Compounds. TID-3513. USAEC.

————. Radioisotopes in Agriculture: Animal Husbandry, Bacteriology, Fertilizer Uptake, Plant Physiology Photosynthesis, and Entomology. TID-3516. USAEC.

————. Radioisotopes in Animal Physiology. TID-3515. USAEC.

————. Utilization of Radioisotopes in Physical and Biological Sciences--General Topics. TID-3519. USAEC.

Special Sources of Information on Isotopes in Industry, Agriculture, Medicine, and Research. USAEC.

SUPPLIERS OF NUCLEONICS EQUIPMENT AND SUPPLIES

Atomic Accessories, Inc., Subsidiary of Baird-Atomic, Inc., 1485 Bayshore Boulevard, San Francisco, California
Baird-Atomic, Inc., 1485 Bayshore Boulevard, San Francisco, California
Central Scientific Company, 1040 Martin Avenue, Santa Clara, California
Nuclear-Chicago Corporation, 441 Cambridge Avenue, Palo Alto, California
Radiation Equipment and Accessories Corporation, 1485 Bayshore Boulevard, San Francisco, California
United States Nuclear Corporation, 801 North Lake Street, Burbank, California
The Welch Scientific Company, 1515 North Sedgwick Street, Chicago, Illinois

equipment list

The equipment listed below may be used for Sessions 5 to 12, 14, 16, and 17. The first two are rate meters and the counting rate in counts per minute is recorded on a panel meter. While they are the most reasonable, they are not generally suited for the accurate measurements required in this course. The remaining units are scalers and will read out the accumulated total of counts.

The equipment improves as the price increases: However, little can be gained by purchasing equipment more refined than the Baird-Atomic Scaler, No. 6 on the list.

	Item		Approximate Price
1.	Cenco No. 7120, Radioactivity Demonstrator (rate meter)		$200
2.	Nuclear-Chicago Corporation Model 1613A Classmaster (rate meter)		200
3.	Radiation Equipment and Accessories Corporation No. 2100 Nuclear Training System		300
4.	Radiation Equipment and Accessories Corporation No. 2300 Nuclear Training System		550
5.	Cenco No. 71208 Scaler and Power Supply	300	
	Cenco No. 71204 End-window Probe	20	
	Cenco No. 71207 Sample Holder	35	
	Cenco No. 71218 G-M Tube, End-window	60	
			415
6.	Baird-Atomic, Inc., No. 123 G-M Scaler	400	
	Baird-Atomic, Inc., No. 822B End-window Stand and Tube	165	
	Baird-Atomic, Inc., Cable No. 15	20	
			585
7.	Nuclear-Chicago Corporation Model 4000 Nuclear Training System		700

The following equipment and supplies are to be used in the sessions as indicated. Quantities will depend upon the number of experimental setups to be used.

Atomic Accessories SVB-84, (Radium D + E) (Sessions 5, 12, and 15)	10
Nuclear-Chicago RCB-1, Iodine-131, 5ml, 10 µc (Sessions 6, 9, 10, and 14)	3 certificates *
Atomic Accessories SCB-1225-6, Bismuth-210 (RaE) (Sessions 7 and 8)	20
Nuclear-Chicago RCB-1, Phosphorus-32, 5ml, 10 µc (Sessions 7, 8, 10, 14, and 17)	3 certificates *
Nuclear-Chicago R5, Carbon-14 (Session 8)	10
Nuclear-Chicago RCB-1, Carbon-14, 5ml, 50 µc (carbon as sodium carbonate) (Session 11)	8 certificates *

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* RCB-1 nuclides are purchased by obtaining certificates:

Nuclear-Chicago No. RCB-1 Radioactive Nuclide Certificate Book for Isotopes (Forty \$2.50 certificates)	\$95

Cenco No. 71875 Landsverk Electroscope (Session 13)	125
Cenco No. 71021 Alpha Ray Tip (Sessions 13 and 15)	10
Atomic Accessories SL-71-2, Sodium-22, 1 µc (Session 14)	6
Atomic Accessories SL-71-12, Thallium-204, 5 µc (Session 14)	6
Surplus Alnico V Magnitron Magnet (Session 14)	
Atomic Accessories SCG-83, Cesium-139 (gamma source) (Session 15)	8

The following equipment is required for Session 15:

Baird-Atomic No. 135 Scaler	1,000
Baird-Atomic No. 821C Gas Flow Counter	200
Baird-Atomic No. 800D Low Background Shield	275
Baird-Atomic No. 255 Proportional Amplifier	250
Baird-Atomic No. 810B Scintillation Detector	1,000
Baird-Atomic No. 9 Cable	15
Baird-Atomic No. 10 Cable	25
Baird-Atomic No. 14 Cable	20
Atomic Accessories No. AGR-28 Gas Regulator	45
Atomic Accessories No. FPG-39 Proportional P-10 Counting Gas	30
Atomic Accessories No. FGG-38 Geiger Counting Gas	30

Atomic Accessories TF1A-27, Air Sample (Session 16)	150
Atomic Accessories Model TFA-67, Flat Filter Papers for Air Samples, 100/pkg. (Session 16)	12
X-ray Film and X-ray Film Holder (Session 17)	
Growing geranium, tomato, or celery plants (Session 17)	

For Session 18 one of the two suggested pieces of equipment may be used:

Cenco No. 71850 Ray Master Cloud Chamber	35

or

Nuclear-Chicago Corporation Model 1413 Cloud Master with High Intensity Lamp	100

The following miscellaneous items are required for many of the experiments:

100 Atomic Accessories AP-12 1-1/4" Planchets	30
Atomic Accessories SPP-69 Sample Spinner	100
Atomic Accessories PRO-42 Propipette	10
Atomic Accessories TMP-74 Micropipettes, 50 Lambdas	5

100 10 mil thick aluminum foil absorbers (Cut size to fit sample and holder)

100 1/32" lead absorbers (Cut size to fit sample and holder)

100 cardboard absorbers (Cut size to fit sample and holder)